Report

Task 4: Problem and Solution Identification and Prioritization for Cameron Run, Alexandria, Virginia

Prepared for

City of Alexandria
Transportation and Engineering Services

February 2016

CH2MHILL®

Baker

Executive Summary

The City of Alexandria, Virginia (the City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project is being implemented in phases by watershed. The watersheds include Hooffs Run, Four Mile Run, Holmes Run, Cameron Run, Taylor Run, Strawberry Run, Potomac River, and Backlick Run.

This report focuses on problem and solution identification (Task 4) for capacity issues in Cameron Run. It summarizes the problem identification steps, solution development, solution scoring, and alternatives analysis. This task has resulted in three watershed-wide alternatives aimed at resolving capacity-related problems in the Cameron Run watershed. Additionally, Task 4 has provided the City with a decision-making process for evaluating the benefits of potential stormwater management (SWM) projects.

The objectives of this phase of the study were to: (1) identify and prioritize capacity problems based on modeling results from Task 2 of this project, and (2) develop and prioritize solutions to address those problems.

The first objective of the study, identifying and prioritizing problems, was accomplished in two steps. The first step included evaluation of each stormwater junction in the drainage network using a scoring system to identify problems based on several criteria, including: the severity of flooding, proximity to critical infrastructure and roadways, city staff and public identification of problems, and opportunity for overland relief. In the next step, high scoring junctions (that is, higher-priority problems) were grouped together to form high-priority problem areas. In total, eight high-priority problem areas were identified in the Cameron Run watershed. Flooding at locations outside of the high-priority problem areas were either flooding at isolated structures, or did not score high based on the problem area scoring criteria. These flooding problems were not addressed in this project.

The second objective involved developing and prioritizing solutions to address capacity limitations within the eight high-priority problem areas. Several strategies were examined to accomplish this objective, including improving conveyance by increasing hydraulic capacity, reducing capacity limitations by adding distributed storage to the system, and reducing stormwater inflows by implementing green infrastructure (GI). Each of these strategies required a different modeling approach. Conveyance improvements were modeled by increasing pipe diameter in key locations within the problem area, storage was added at storage nodes based on a preliminary-siting exercise, and GI was modeled as a reduction in impervious area at three different implementation levels (high, medium, and low). A single model run was set up for each strategy including solutions for all eight high-priority problem areas and the results were compiled for the alternative and prioritization evaluation. Solutions were evaluated based on several criteria, including drainage improvement/flood reduction, environmental compliance, sustainability and social benefits, asset management and maintenance implications, constructability, and public acceptance. Planning-level capital costs were developed for each solution to facilitate a benefit/cost analysis and prioritization process.

The results of the solution identification and prioritization analysis show the following:

- Solution technology performance:
  - GI generally has the greatest overall benefit as defined by the solution evaluation scoring system described in this report.
  - Conveyance solutions and storage solutions generally provide the greatest flood reduction of the technologies and approaches analyzed in Cameron Run.
  - Combination of conveyance or storage projects and GI generally provides the greatest benefit and flood reduction.

- Costs:
  - Low to medium levels of GI implementation generally has the greatest benefit/cost score but do not usually meet minimum threshold for flood reduction.
  - Conveyance and storage projects generally provide the most economical stormwater volume reduction in terms of dollars per gallon of flood reduction within a high-priority problem area.
  - Combination of conveyance and GI generally provides the greatest overall benefit/cost score.

The following three watershed-wide alternatives were developed:

- Alternative 1: Most cost-effective solution for each problem area (lowest $/gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to address the worst problem areas to the extent practicable

The results for each alternative generally reflects the objective of that particular alternative. A summary of the results is provided in Table ES-1.

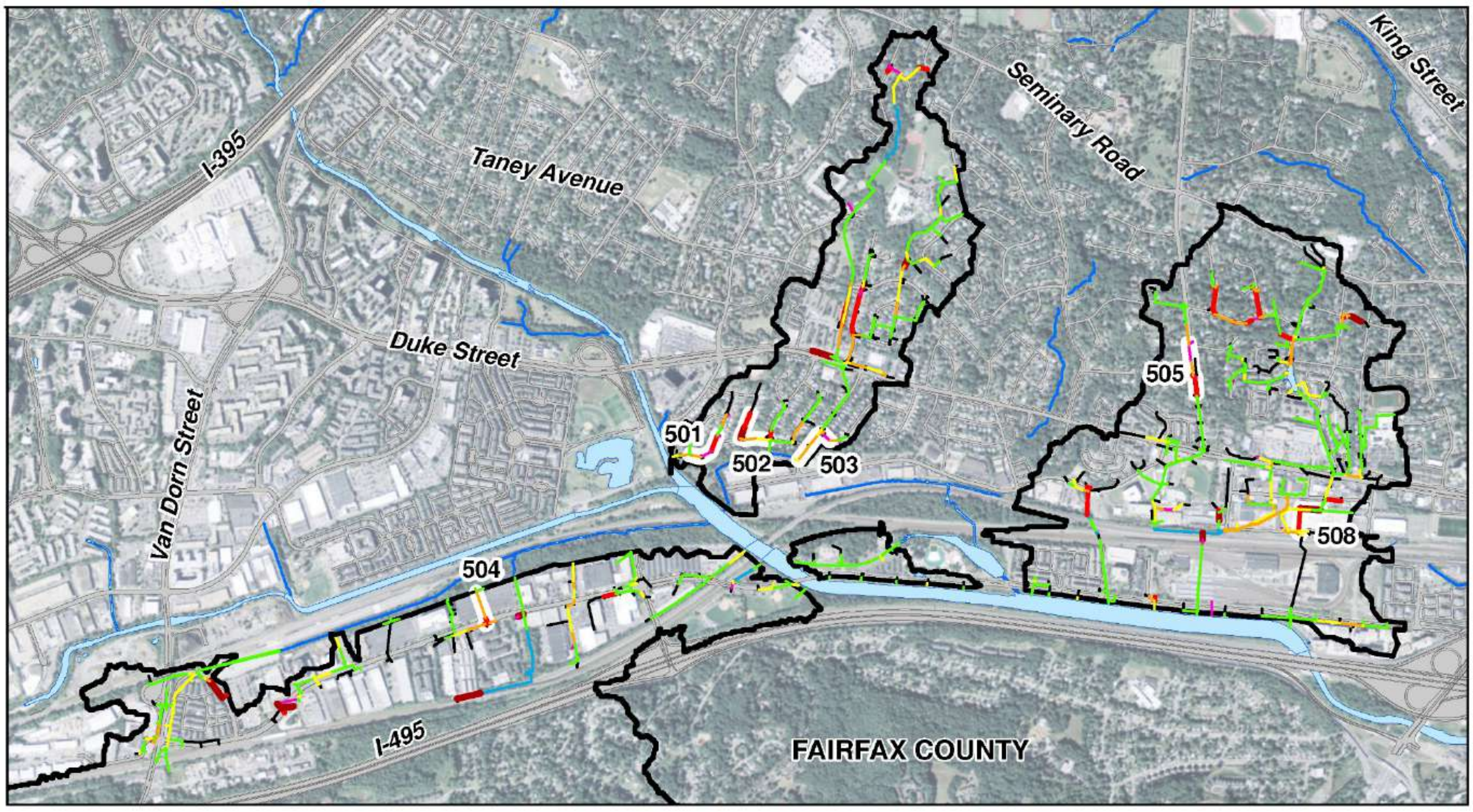
TABLE ES-1
Watershed-wide Alternatives Scoring and Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Alternative 1 - Best Cost Efficiency	Alternative 2 - Best Benefit/Cost Ratio	Alternative 3 – Highest-priority Problems
Total Capital Cost ($ Millions)	$3.65	$3.39	$4.57
Total Benefit Score	360	394	410
Overall Benefit/Cost	99	116	90
Total Flood Reduction (MG)	2.266	1.126	2.669
Cost of Flood Reduction ($/gallon)	$1.61	$3.01	$1.71

Note:
MG - million gallons

Alternative 3 was focused on providing relief in six highest-priority problem areas and included more than one solution for the two highest-priority problem areas. Alternative 3 provides almost 18 percent more flood volume reduction than Alternative 1 and over twice as much as Alternative 2; however, Alternative 3 has the lowest overall benefit/cost ratio among the three solutions. Although Alternative 2 has the highest overall benefit/cost ratio results, its cost of flood reduction is the highest at $3.01 per gallon; almost twice as much as the other two alternatives. Alternative 1 provides the second highest overall benefit/cost ratio and total flood reduction at the lowest cost per gallon among the three alternatives. Comparably, Alternative 1 provides relatively high benefits with the lowest unit cost to reduce flood; therefore, Alternative 1 is the most optimal cost-effective watershed-wide alternative considering the trade-off between benefits and cost. Model simulation results for the existing condition scenario and the Alternative 1 watershed-wide solution are presented in Figures ES-1 and ES-2.

FIGURE ES-1
Existing Condition Model Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.1 - 1,000
- 1,000 - 10,000
- 10,000 - 1,018,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Existing Conditions Model Results and High Priority Problem Areas (West, Center, and North subwatersheds)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 1,000 2,000 4,000
Feet
N

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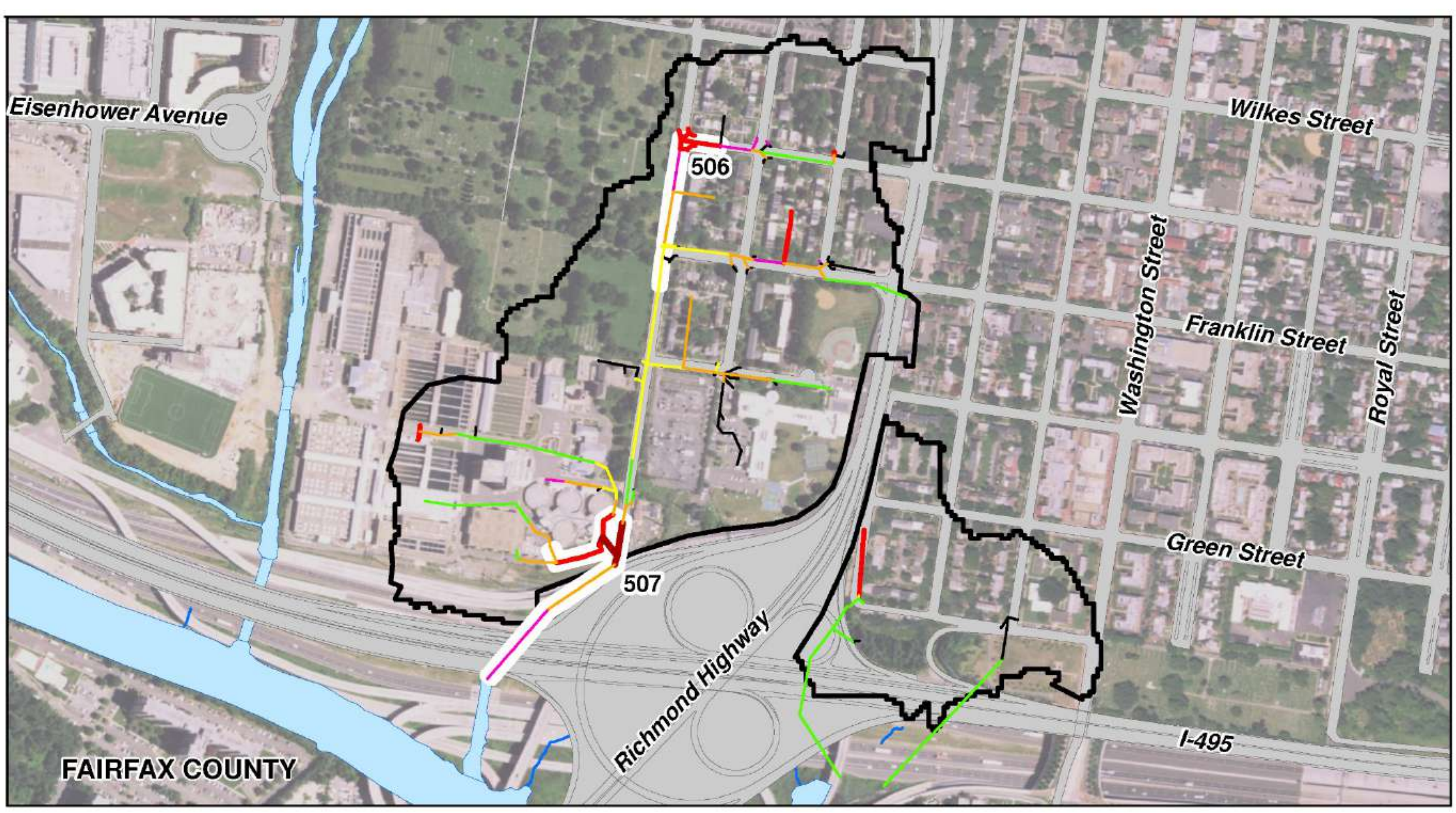

Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.1 - 1,000
- 1,000 - 10,000
- 10,000 - 21,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Existing Conditions Model Results and High Priority Problem Areas (Southeast subwatershed)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 250 500 1,000
Feet
N

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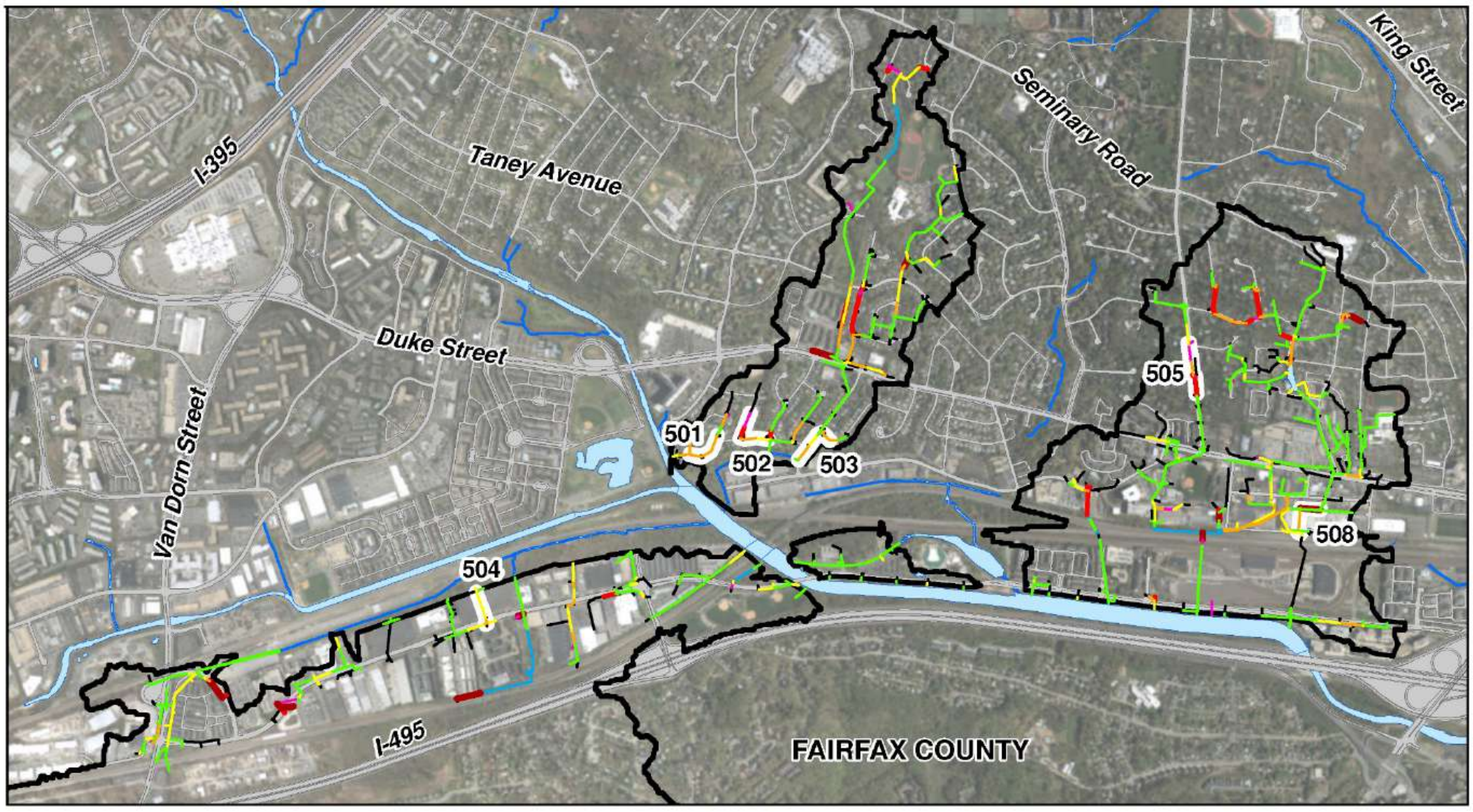
FIGURE ES-2
Alternative 1: Best Cost Efficiency Model Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 1,017,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Watershed-wide Alternative 1: Best Cost Efficiency Model Results and High Priority Problem Areas (West, Center, and North subwatersheds)

Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 1,000 2,000 4,000
Feet

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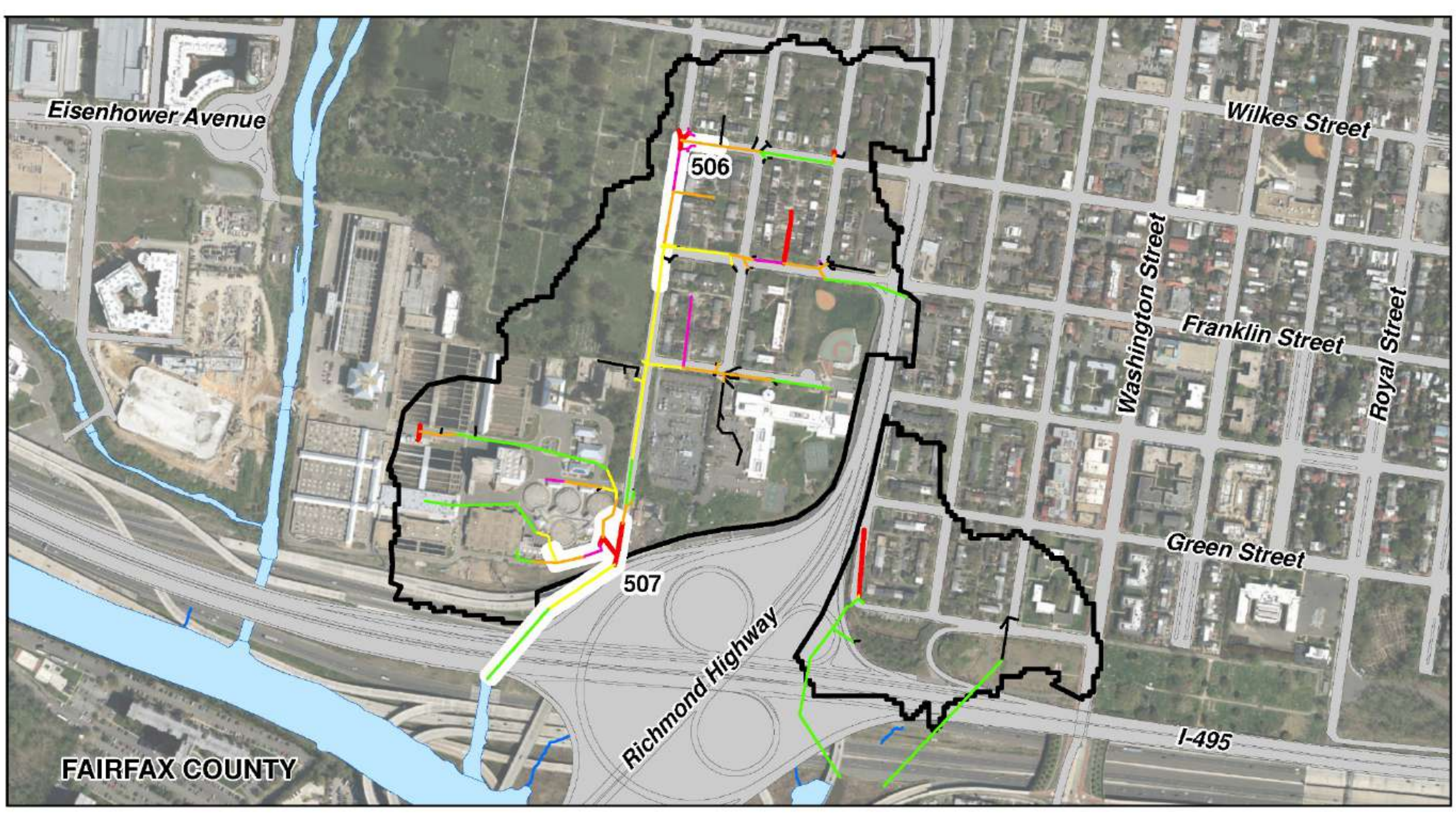

Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 7,500
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Watershed-wide Alternative 1: Best Cost Efficiency Model Results and High Priority Problem Areas (Southeast subwatersheds)

Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 250 500 1,000
Feet

N

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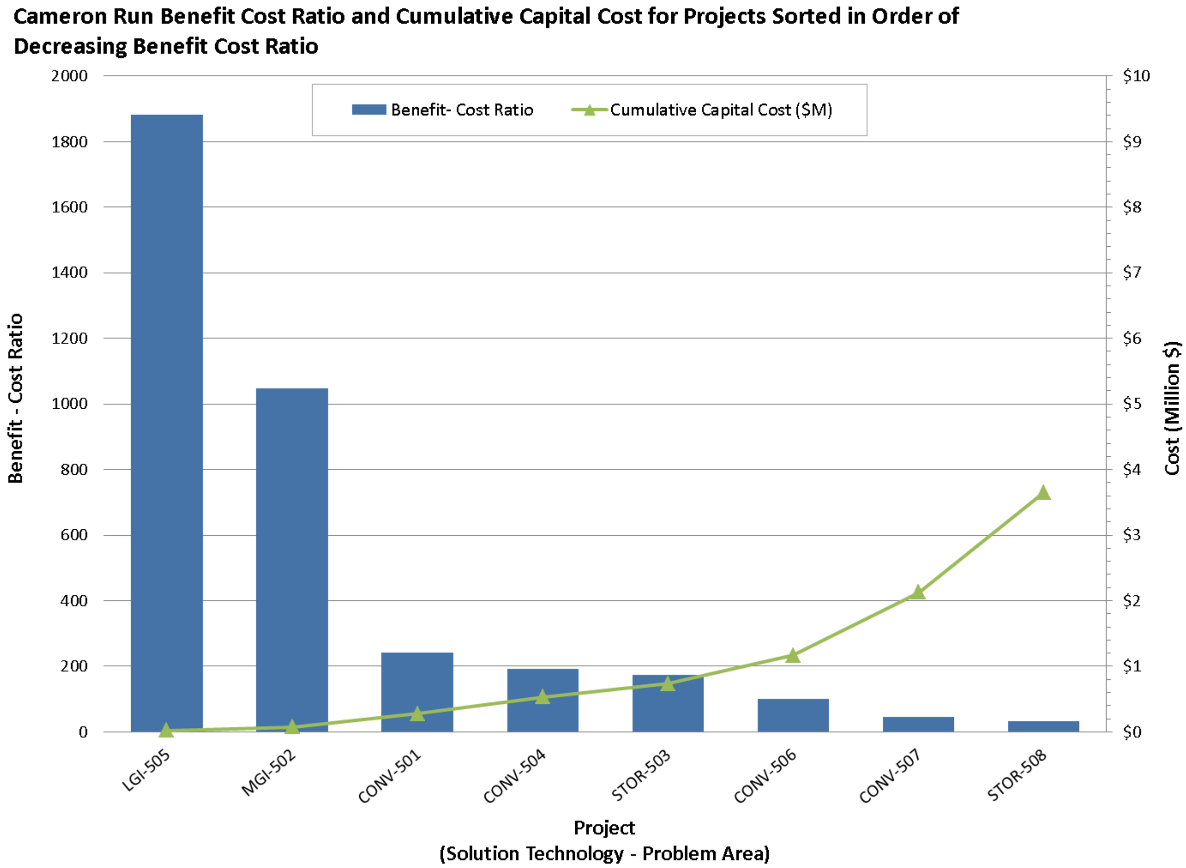
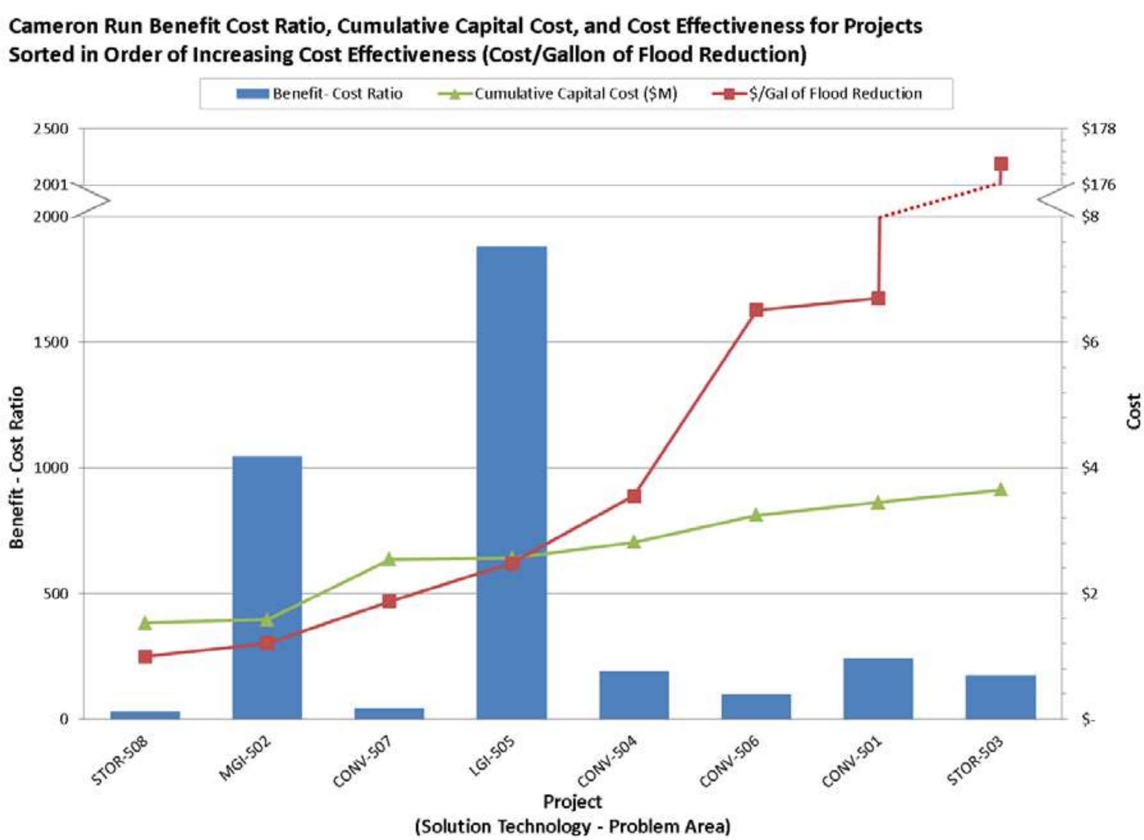
When developing a capital improvement plan, the benefit/cost or cost efficiency ($/gallon of flood reduction) are typically used to guide the order in which projects are implemented. Prioritization results for Alternative 2 are presented in Figure ES-3. The top chart shows the total benefit score and the cumulative capital cost of the alternative. The solutions are provided in order of decreasing benefit/cost ratio; solutions with the greatest benefit/cost are presented on the left and solutions with the lowest benefit/ cost are presented on the right. The bottom chart shows the benefit/cost ratio for each solution in the watershed-wide alternative in order of increasing cost/gallon of flood reduction. Both charts show the cumulative capital cost plotted on the secondary axis. The solutions on both charts are named by the technology: conveyance (CONV), storage (STOR), low GI (LGI), medium GI (MGI), or high GI (HGI), and the problem area number.

It should be noted that the model does not include analysis on private property, but applies assumed runoff loads as inputs to the public conveyance system. The City chose not to include existing private or public stormwater management facilities upstream of the modeled collection system because of the limited available information on these facilities and a concern that the facilities may not be performing as designed. When the City moves forward into detailed evaluation and design of selected projects, it will be important to fully evaluate and account for the benefits of any existing stormwater management facilities.

The hydraulic modeling results and costs presented in this report should be reviewed with the understanding that several assumptions were made to fill data gaps in the hydraulic model, and proposed solutions and costs were developed on a planning level.

FIGURE ES-3
Alternative 1: Best Cost Efficiency Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run





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Acronyms and Abbreviations

bgs	below ground surface
cfs	cubic feet per second
City	City of Alexandria, Virginia
ft^2	square feet
ft^3	cubic feet
GI	green infrastructure
HGL	hydraulic grade line
HGI	high green infrastructure
hrs	hours
ID	identification
IDF	intensity-duration-frequency
LF	linear feet
LGI	low green infrastructure
MG	million gallons
MGI	medium green infrastructure
ROW	right-of-way
SWM	stormwater management
TM	technical memorandum

SECTION 1

Introduction

The City of Alexandria, Virginia (the City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project is being implemented in phases by watershed. This report focuses on problem and solution identification (Task 4) for capacity issues in Cameron Run. City of Alexandria watersheds are shown on Figure 1-1.

1.1 Background

The project consists of four major subtasks related to the model development and modeling. These four tasks and related technical memorandums (TMs) are described as follows:

- Task 1 – Review and propose revisions to the City's stormwater design criteria.
  - *Updated Precipitation Frequency Results and Synthesis of New IDF Curves for the City of Alexandria, Virginia* (CH2M HILL, 2009a)
  - *Sea Level Rise Potential for the City of Alexandria, Virginia* (CH2M HILL, 2009b)
  - *Rainfall Frequency and Global Change Model Options for the City of Alexandria* (CH2M HILL, 2011)
- Task 2 – Analyze the City's stormwater collection system capacity.
  - *Inlet Capacity Analysis for City of Alexandria Storm Sewer Capacity Analysis* (CH2M HILL, 2012)
  - *Stormwater Capacity Analysis for Cameron Run Watershed, City of Alexandria, Virginia* (CH2M HILL & Baker, 2016)
- Task 3 – Survey collection system facilities on pipes 24 inches and larger to fill data gaps.[1]
  - *City of Alexandria Storm Sewer Capacity Analysis – Cameron Run Condition Assessment* (Baker, 2014)
- Task 4 – Identify problem areas and suggest solutions.
  - *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014)

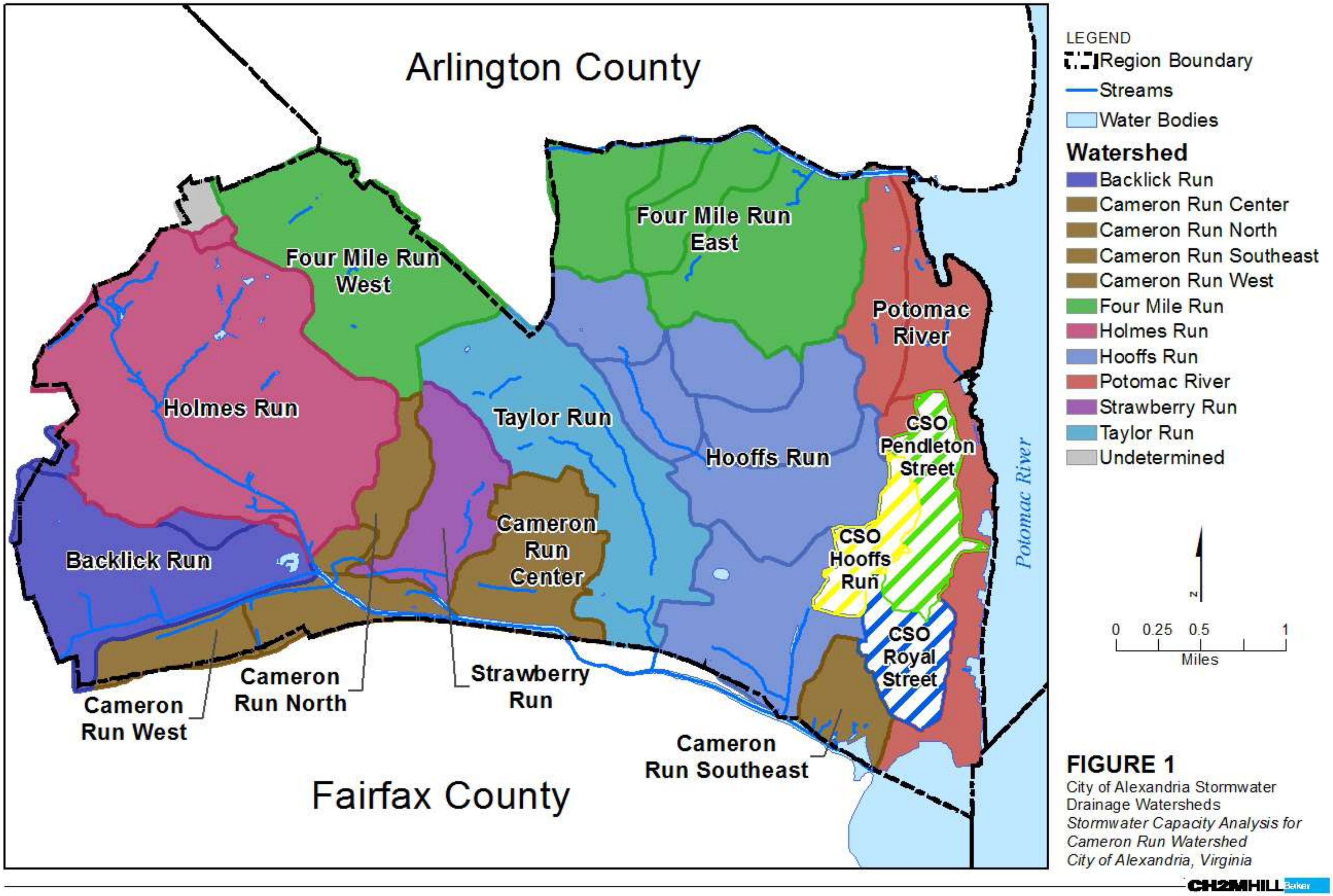
1.2 Objectives

Tasks 1 through 3 focused on model development and capacity analysis of the existing system. The purpose of Task 4 is to identify and prioritize problems modeled during the Task 2 capacity analysis and to suggest and prioritize conveyance, storage, and green infrastructure (GI) solutions to resolve the identified capacity limitations.

This report describes the methodology and results of Task 4 for the stormwater collection system in the Cameron Run watershed. Figure 1-1 presents the City's stormwater drainage watersheds.

[1] Though originally intended to improve data quality where the model predicted capacity limitations, the scope of Task 3 was expanded, and field survey was completed before Task 2 to fill data gaps and to improve the model development process.

FIGURE 1-1
Stormwater Drainage Watersheds, City of Alexandria, Virginia
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



SECTION 2

Approach

The approach to identifying and prioritizing problems and solutions included several distinct steps: identification and prioritization of problems, development and modeling of solutions, prioritization of solutions and, finally, development of watershed-wide scenarios.

This section describes this approach, which is broken into two major components: prioritization and modeling.

2.1 Prioritization

The focus of Task 4 is prioritization of problem areas based on Task 2 modeling results, development of solutions to resolve the problem areas, then prioritization of those solutions. Before beginning the Task 4 analysis, City staff and CH2M HILL and Michael Baker consultants convened in a workshop on November 14, 2012 to discuss the objectives, approach, and desired outcomes of this phase of the project. The major objectives of the workshop were to define the prioritization process, identify the key evaluation criteria for scoring and ranking problems and solutions, and define relative criteria weights. The following prioritization process is similar for both problems and solutions:

- **Define evaluation criteria**: Evaluation criteria for problems and solutions were defined during the Task 4 workshop with input from City Engineering & Design, Office of Environmental Quality, and Maintenance Divisions of Transportation and Engineering Services staff. These criteria, which are summarized in this report, were used to assess the severity of problems and the benefit of solutions.
- **Weight evaluation criteria**: Each evaluation criterion was assigned a weight (0 to 100) by Task 4 workshop participants. The weights quantify the relative importance of each evaluation criteria and build a defensible foundation for problem and solution ranking.
- **Define scoring system**: A scoring system was developed for each evaluation criteria. This provided a method for ranking problems and solutions within evaluation criteria. Scoring systems for problem area and solution evaluation criteria are defined in this report.
- **Score and rank alternatives**: Problems and solutions were scored and ranked using the evaluation criteria scoring systems, which are described in the TM, *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014) and include:
  - *Score and Rank Problems:* A score of 0 through 10 was assigned to stormwater junctions in the modeled system for each evaluation criteria. Weights were then applied to the score calculated for each evaluation criteria to come up with an overall weighted score for each junction. The overall score was used to rank problems, then high-priority problem areas were identified as groupings of hydraulically-connected junctions and pipes. Solutions were investigated for the highest-priority problem areas.
  - *Score and Rank Solutions*: Solutions were developed for high-priority problem areas identified in the previous step. A score of 0 through 10 was assigned to solutions for each evaluation criteria. Then the weights were applied to the score calculated for each evaluation criteria to calculate an overall weighted-benefit score. Solutions were ranked based on the overall score as well as the cost/benefit score, which is the overall benefit score divided by the capital cost of the solution. The solution evaluation is presented at the end of this report.
- **Perform "what-if" analysis to refine process**: After completing the prioritization, the process was examined to ensure the results met the City's expectations. The outcome of this step was the inclusion of a 22 percent minimum threshold for flood volume reduction (any project that produced less than 22 percent reduction in volume of flooding was eliminated) to help focus the solution identification process. This threshold was selected by City staff based on best engineering judgment.

- **Evaluate watershed-wide scenarios**: Once individual solutions were evaluated, the solutions were grouped into three alternative watershed-wide scenarios. The scenarios were scored by summing scores and costs of individual projects for comparison. The purpose of taking this watershed-wide look was to evaluate the solutions in a holistic, system-wide manner to evaluate the impacts of implementing various solutions across the system. This also supports the selection of solutions that will provide the greatest benefit for the least cost.

2.1.1 Problem Area Evaluation

The problem area evaluation focused on identifying flooding problems that are extreme and/or in proximity to critical facilities. Though model results were presented for pipes and not junctions in the Stormwater Capacity Analysis (Task 2), flooding occurs at a junction and not along the length of the pipe. Therefore, stormwater junctions in the hydraulic model, not pipe segments, were scored for each of the problem area evaluation criteria. Raw scores for each criterion ranged from 0 to 10, 0 indicating the junction is not a priority and/or the evaluation criteria is not applicable, and 10 indicating the junction is a high-priority. The problem area evaluation criteria includes the following:

- Urban drainage/flooding
- Identification of problems by the public
- Identification of problems by city staff
- Proximity to critical infrastructure
- Proximity to critical roadways
- Opportunity for overland relief

Detailed descriptions of the problem-scoring systems used in this evaluation are provided in the TM, *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014). The weighted score was computed using the raw score and normalized percent weight. Evaluation criteria and weights developed and agreed upon during the Task 4 Workshop are presented in Table 2-1.

TABLE 2-1
Problem Area Evaluation Criteria and Weights
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area Evaluation Criteria	Weight	Normalized % Weight
Urban Drainage/Flooding	90	23.1
Public ID of Problem	73	18.8
City Staff ID of Problem	75	19.3
Proximity to Critical Infrastructure	58	14.9
Proximity to Critical Roadways	38	9.8
Opportunity for Overland Relief	55	14.1
Total	**389**	**100**

Note:
ID = Identification

After computing the weighted score for each junction, high-priority problem areas were identified as hydraulically-connected groupings of junctions and pipes for the junctions with scores over 30. Scoring was based on results from the Task 2 model of the 10-year, 24-hour storm generated using the existing intensity-duration-frequency (IDF) curve. The results of the problem area evaluation are presented in Section 3, Problem Identification.

The goal of delineating high-priority problem areas was to identify groupings of stormwater pipes causing capacity limitations so that conveyance, storage, and GI solutions could be developed for the area. This task was accomplished by starting with the highest-ranked junction score. This score indicated it was the worst problem based on the problem area identification evaluation criteria, and based on the review of the surrounding drainage network and model results to identify the pipes and junctions related to that high problem score. A polygon surrounding all the pipes related to the capacity limitation was digitized in ArcMap and was assigned a unique identifier. After completing this process for the highest-ranked junction score, the network and model results for the next-highest score were examined, and a new problem area was digitized. However, if the junction with the next highest-score was already captured in the first high-priority area, it was skipped. This process was repeated for junctions with a score above 30, or the top 8 percent of junctions with a score over 0. Flooding at locations outside of the high-priority problem areas were either flooding at isolated structures, or did not score high based on the problem area scoring criteria. These flooding problems were not addressed by solutions in this project.

2.1.2 Solution Evaluation

Solutions were developed to resolve or improve capacity limitations in the highest-priority problem areas. Three different technologies were evaluated: conveyance, storage, and GI. Modeling results, described in detail in the following sections, were used in conjunction with additional data from the City (for example, geospatial data on roads and critical infrastructure, capital improvement plans, maintenance plans) to score solutions for each of the following solution evaluation criteria:

- Urban drainage/flooding
- Environmental compliance
- EcoCity goals/sustainability
- Social benefits
- Integrated asset management
- City-wide maintenance implications
- Constructability
- Public acceptability

Detailed descriptions of the solution scoring systems used in this evaluation are provided in the TM, *Task 4 Evaluation Criteria Scoring Systems* (CH2M HILL, 2014). The weighted score was computed using the raw score and normalized percent weight. Table 2-2 presents the evaluation criteria and weights agreed upon during the Task 4 workshop.

TABLE 2-2
Solution Evaluation Criteria and Weights
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Solution Evaluation Criteria	Weight	Normalized % Weight
Urban Drainage/Flooding	95	17.1
Environmental Compliance	93	16.8
EcoCity Goals/Sustainability	50	9.0
Social Benefits	40	7.2
Integrated Asset Management	73	13.2
City-wide Maintenance Implications	90	16.2
Constructability	60	10.8
Public Acceptability	53	9.6
Total	**554**	**100**

2.2 Modeling

To support the Task 4 analysis, the Cameron Run watershed stormwater capacity was analyzed using commercially available and public domain computer models widely used and industry-accepted. The details of the hydrologic and hydraulic modeling are documented in the Task 2 TM, *Stormwater Capacity Analysis for Cameron Run Watershed, City of Alexandria, Virginia* (CH2M HILL & Baker, 2016). The existing conditions model of the 10-year, 24-hour design storm based on the City's existing IDF curve served as the basis for modeling in the Task 4 analysis.

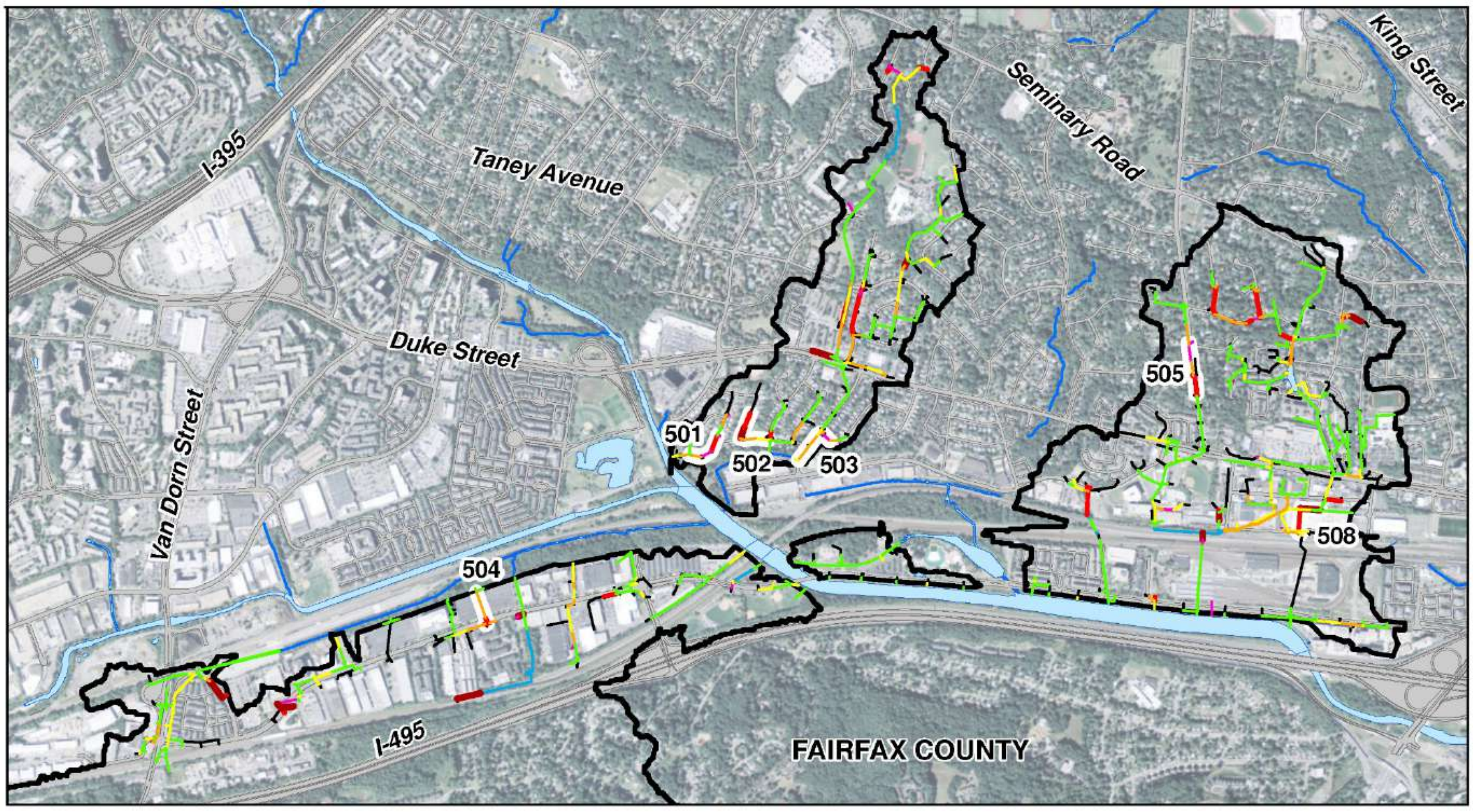
Figure 2-1 and Table 2-3 present the Task 2 results for reference.

TABLE 2-3
Summary of Task 2 Model Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Existing Capacity Results			
	Conduit Length (LF)	**Percent of Total Length (%)**	**Total Duration (hrs)**	**Total Volume (ft^3)[b]**
Sufficient Capacity	47,139	57.4	-	-
Surcharged[a]	13,653	16.6	453	-
Insufficient Freeboard	11,252	13.7	-	-
Flooded	10,042	12.2	73	2,117,542

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits have insufficient freeboard or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

FIGURE 2-1
Existing Condition Model Results and High-Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.1 - 1,000
- 1,000 - 10,000
- 10,000 - 1,018,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Existing Conditions Model Results and High Priority Problem Areas (West, Center, and North subwatersheds)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 1,000 2,000 4,000
Feet

N

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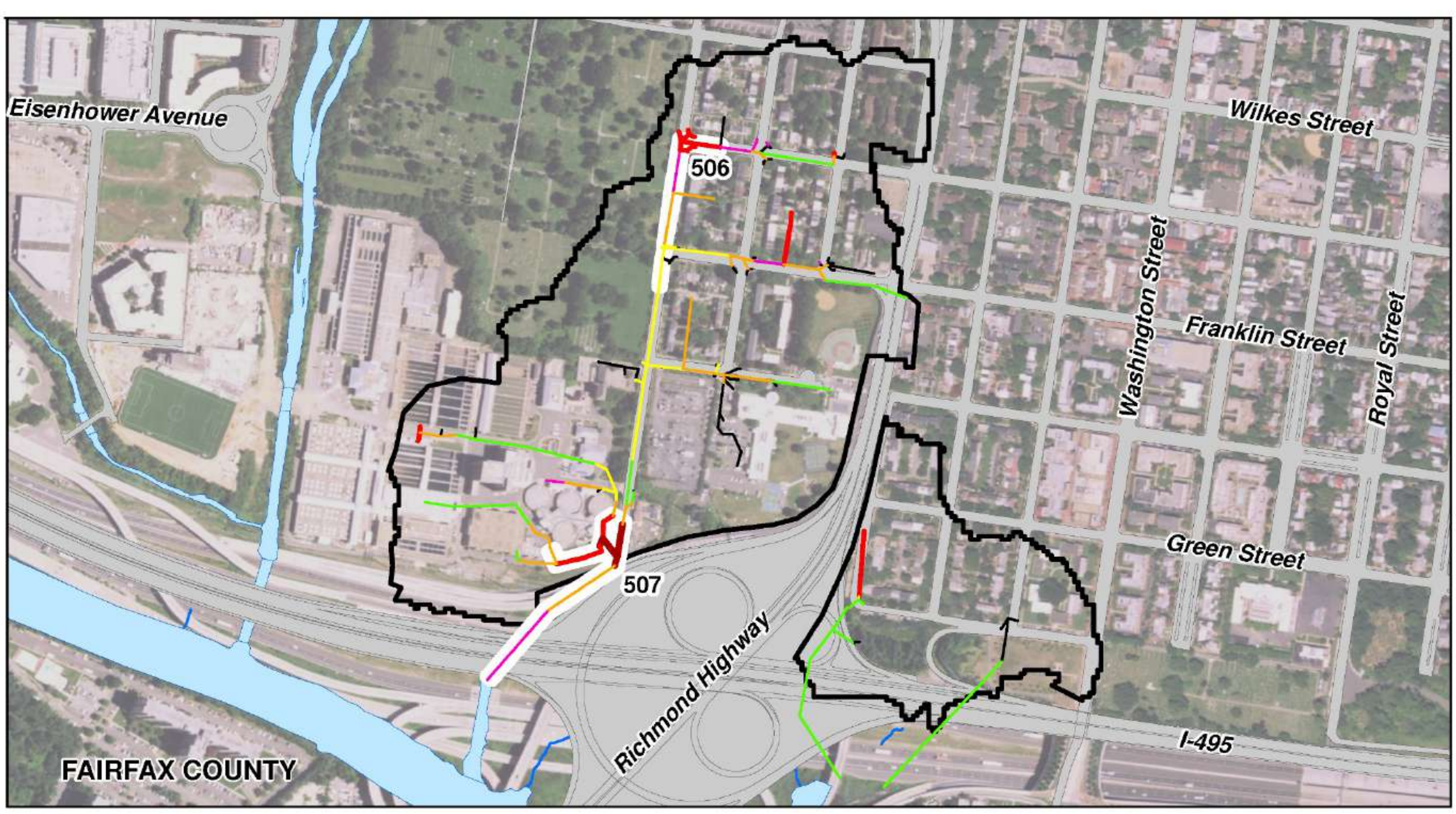

Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.1 - 1,000
- 1,000 - 10,000
- 10,000 - 21,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Existing Conditions Model Results and High Priority Problem Areas (Southeast subwatershed)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 250 500 1,000
Feet

N

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2.2.1 Baseline Improvements and Major Capacity Solutions

In Hooffs Run, the first watershed analyzed for this study, several baseline improvements and major capacity solutions were identified and addressed before evaluating solutions in the rest of the system. The goal of identifying baseline improvements was to remove hydraulic limitations that may have negatively affected the ability to model solutions. A similar evaluation was conducted for Cameron Run to determine whether baseline improvements and major capacity solutions were needed.

Profiles of the Cameron Run existing conditions model results were reviewed to identify significant changes in diameter or slope, over relatively short distances where there was also a sudden increase in the hydraulic grade line. In addition to reviewing the profiles, the data sources for invert and diameter information were reviewed. There were no locations identified in the Cameron Run watershed that required baseline improvements. In addition, no locations were identified within the Cameron Run watershed where extreme capacity limitations caused long backwater conditions and substantial flooding in the system. Therefore, there was no need for developing solutions for major capacity problems.

2.2.2 Alternative Solutions

The purpose of this task was to identify and evaluate corrective measures that could be undertaken to reduce flooding and improve stormwater quality through the use of GI practices. In addition, there is the potential to achieve other ancillary benefits such as improved aesthetics, urban-heat-island reduction, and carbon capture through context-sensitive solutions. Potential solutions were developed for each of the following project types or technologies, where applicable:

- Conveyance improvements
- Storage (modeled as underground storage, but could also be implemented as above ground storage or other conventional stormwater management approaches)
- GI

The goal of the conveyance solutions was to evaluate the impact of increased conveyance capacity on flooding and surcharge in the high-priority problem areas. Conveyance improvements were modeled in xpswmm by increasing pipe diameter up to 0.1-foot below ground surface (bgs). The invert elevations and alignment of existing pipes were not altered, so pipe slope did not change from existing conditions. Because the goal of this evaluation was not to design solutions but to evaluate potential strategies and technologies, more detailed design will be required to develop fully implementable projects, including adjusting pipe shapes, providing parallel pipes, and providing for adequate ground cover.

The storage solutions involved evaluating the potential for new detention or retention facilities or offline storage for high-priority problem areas. Because of the dense urban development prevalent in the City, conventional stormwater management (SWM) practices were assumed to be limited to offline subsurface storage facilities in the hydraulic model. Opportunities for subsurface storage were identified in open spaces (such as parking lots, green spaces, and grassed medians), with a preference for City-owned properties. Storage was modeled in xpswmm using storage nodes and weirs to model the overflow from a manhole into storage. The maximum storage size was determined by measuring the surface area of the open space available for storage and estimating the storage depth based on the manhole to which the storage system would be dewatered. It was assumed that storage should be a minimum 3 feet deep and a maximum 10 feet deep to maintain reasonable construction costs. Additionally, storage was only considered if gravity dewatering to a manhole within 1,000 feet was possible. Storage facilities would not be dewatered until the system had capacity to convey the stored flow. Because the focus of the modeling was to identify capacity limitations and flooding problems, storage dewatering was not evaluated in this analysis.

GI was evaluated at three different implementation levels: low, medium, and high. In the xpswmm model, GI was modeled by reducing impervious cover in model subcatchments. The low implementation level was modeled as a 10 percent reduction in impervious area, the medium at a 30 percent reduction, and the high at a 50 percent reduction. During development of the modeling approach, soil and depression storage parameters were evaluated for sensitivity in the model. Ideally, these parameters would be adjusted to more accurately represent the physics of GI performance in the field. However, this level of detailed modeling was beyond the scope of this study, and infiltration parameters were not altered when modeling GI.

Table 2-4 describes the modeling approach and basic assumptions for each of the solution technologies. Solutions developed for each high-priority problem area are detailed in Section 4, Solution Identification.

TABLE 2-4
Description of Solution Modeling Approaches and Assumptions
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Solution Technology/Strategy	Modeling Approach	Basic Assumptions
Conveyance	Increase Pipe Diameter	Use existing slope and pipe alignment. Increase pipe diameter to a maximum of 0.1 foot bgs. Add barrels as necessary.
Storage	Add storage node with weir to convey flow into storage	Storage depth is between 3 feet and 10 feet bgs. Gravity dewatering is required. A 20-foot-long weir to storage with discharge coefficient of 3 is required. Only surcharged flow will be sent to storage.
Green Infrastructure	Decrease catchment impervious area	Low implementation: 10 percent reduction in impervious area. Medium implementation: 30 percent reduction in impervious area. High implementation: 50 percent reduction in impervious area.

Solution alternatives were modeled in xpswmm. The basis for the solution models was the Task 2 existing conditions model.

Alternative solutions were evaluated in five different models, one for each technology/strategy:

- Conveyance solutions model
- Storage solutions model
- Low GI implementation model
- Medium GI implementation model
- High GI implementation model

This approach has limitations because several projects are in proximity to one another; therefore, the hydraulics are inextricably linked. However, because of the number of solutions and technologies being evaluated, evaluating each project independently was not within the scope of the analysis.

SECTION 3

Problem Identification

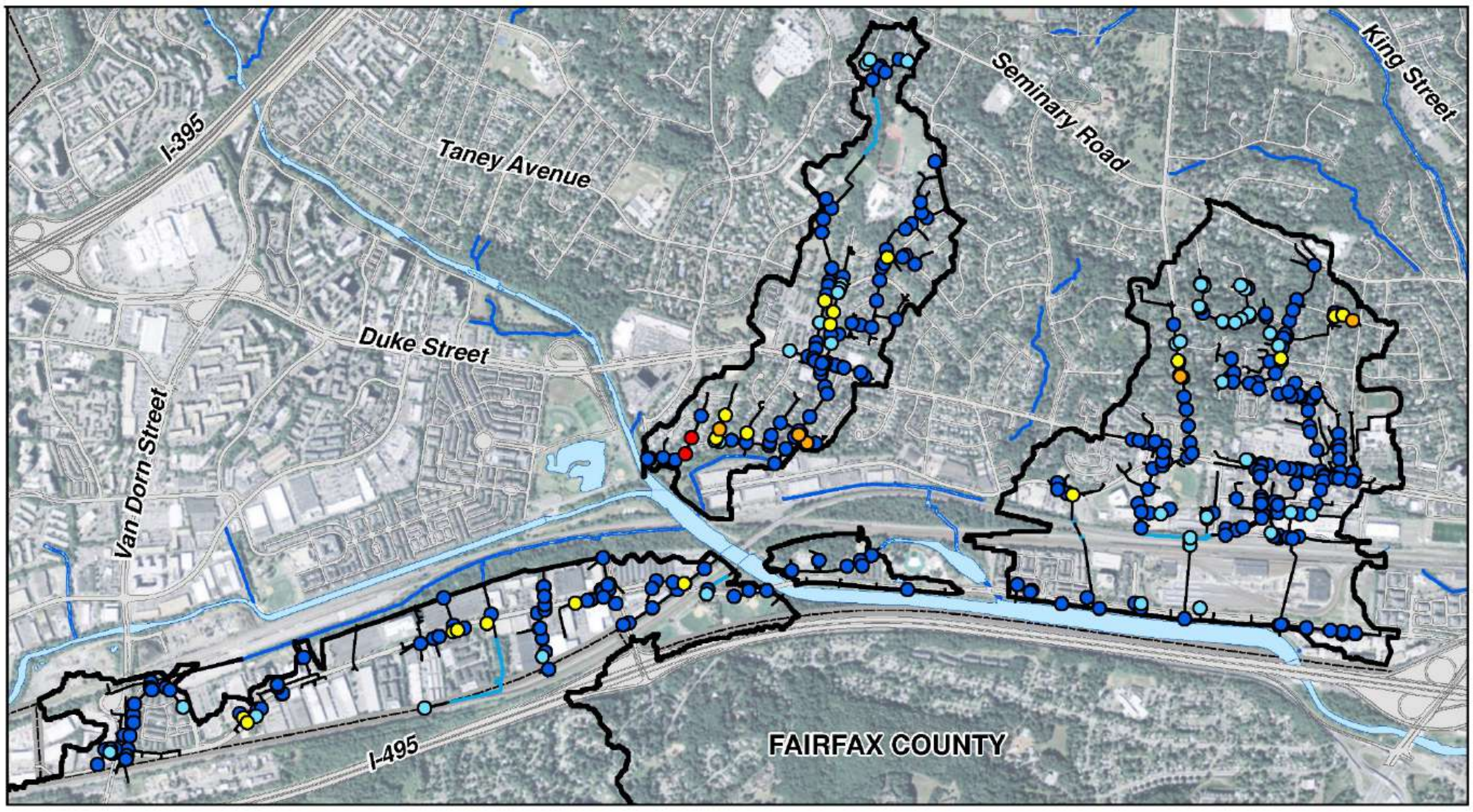
The purpose of the problem identification task was to assign a score to structures in the stormwater drainage network so that high-priority problem areas could be identified. Solution alternatives were developed for high-priority problem areas in the Cameron Run watershed. Junctions were scored for each of the problem area evaluation criteria. Table 3-1 shows the distribution of scores across the 1,456 stormwater junctions that were modeled in Cameron Run. These results were generated using the Task 2 existing condition model (existing IDF and existing boundary conditions). Figure 3-1 provides a map of the junction scores.

TABLE 3-1
Cameron Run Problem ID Scores
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem ID Score	Count of Junctions	% of Total
0	990	68.0
0.1 – 20	372	25.5
20.1 – 30	58	4.0
30.1 – 40	29	2.0
40.1 – 50	5	0.3
>50	2	0.1
Total	**1,456**	**100**

After scoring individual junctions, high-priority problem areas were identified as groupings of hydraulically-connected junctions and pipes in proximity to one another. Junction scores and high-priority problem area delineations were based on the existing conditions model results presented in Task 2 TM (CH2M HILL & Baker, 2016). A total of eight high-priority problem areas were identified in Cameron Run and are shown on Figure 3-2.

FIGURE 3-1
Junction Scores for Existing Conditions Model
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



Legend

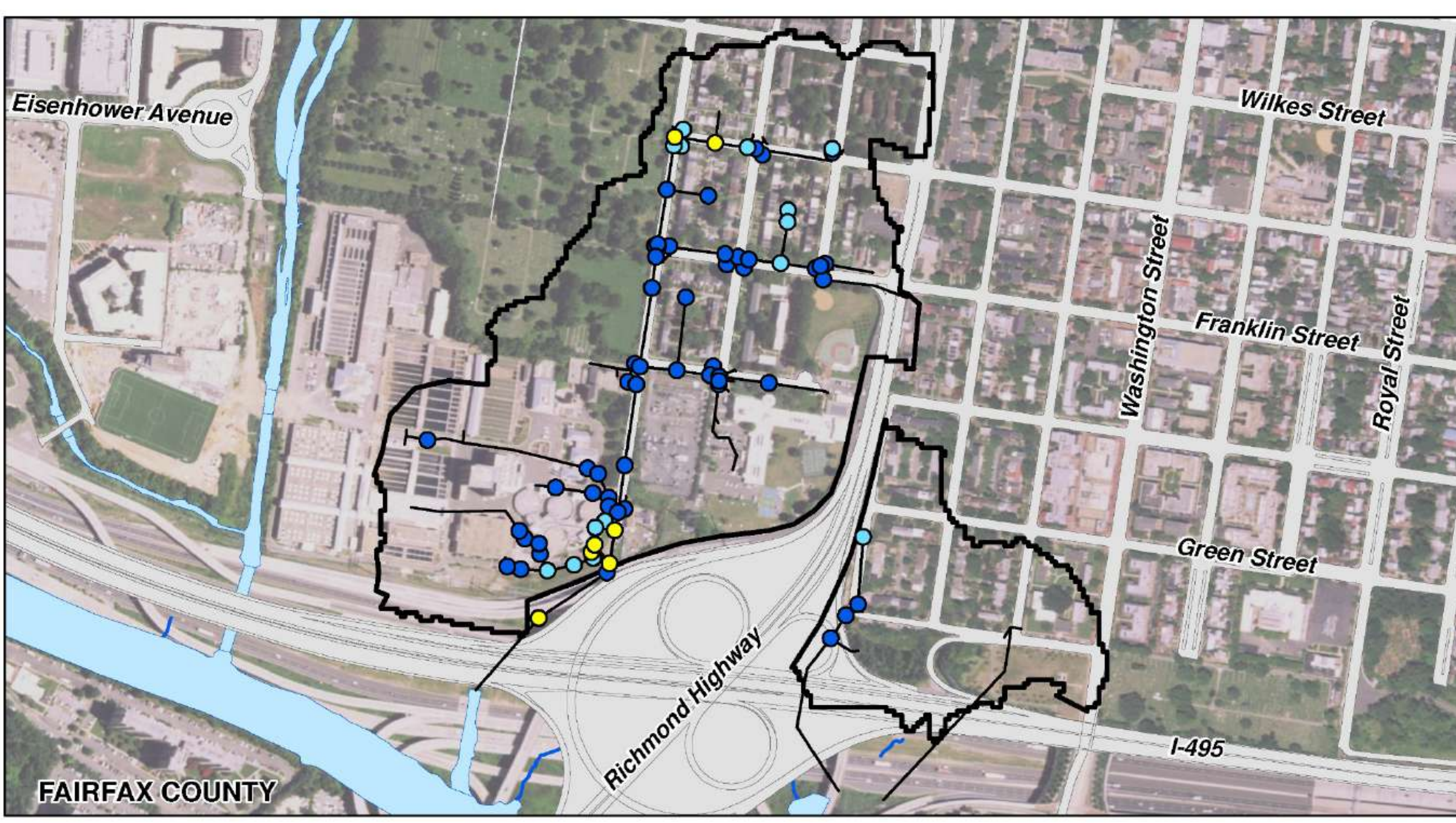
●	0.1 - 20	—	Gravity Mains
●	20.1 - 30	—	Modeled Streams
●	30.1 - 40	—	City of Alexandria Streams
●	40.1 - 50	▭	Water Bodies
●	> 50	▭	Subwatersheds

Junction Scores for Existing Conditions Model
(West, Center, and North subwatersheds)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 1,000 2,000 4,000
Feet

N

CH2MHILL Baker



Legend

●	0.1 - 20	—	Gravity Mains
●	20.1 - 30	—	Modeled Streams
●	30.1 - 40	—	City of Alexandria Streams
●	40.1 - 50	▭	Water Bodies
●	> 50	▭	Subwatersheds

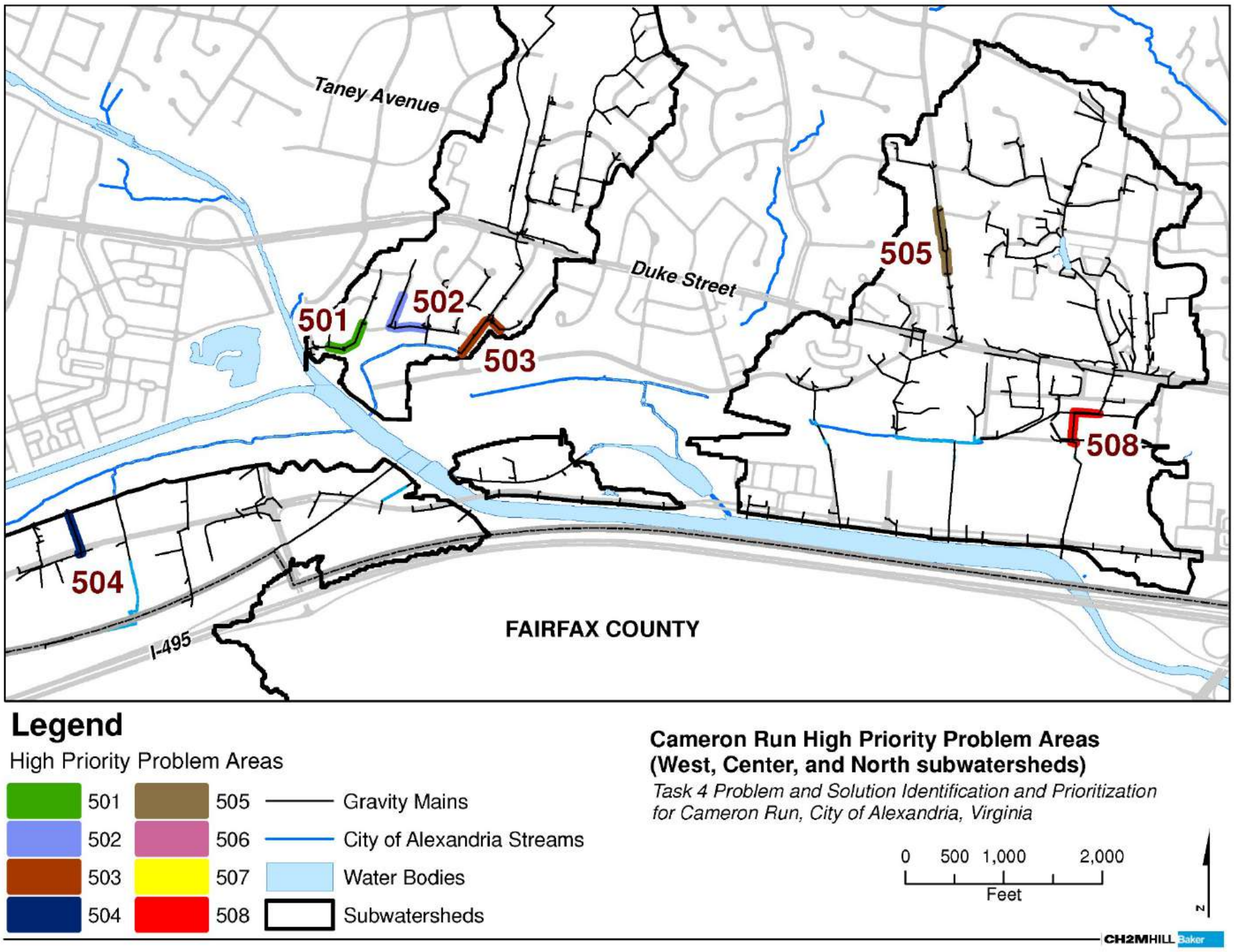
Junction Scores for Existing Conditions Model
(Southeast subwatershed)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

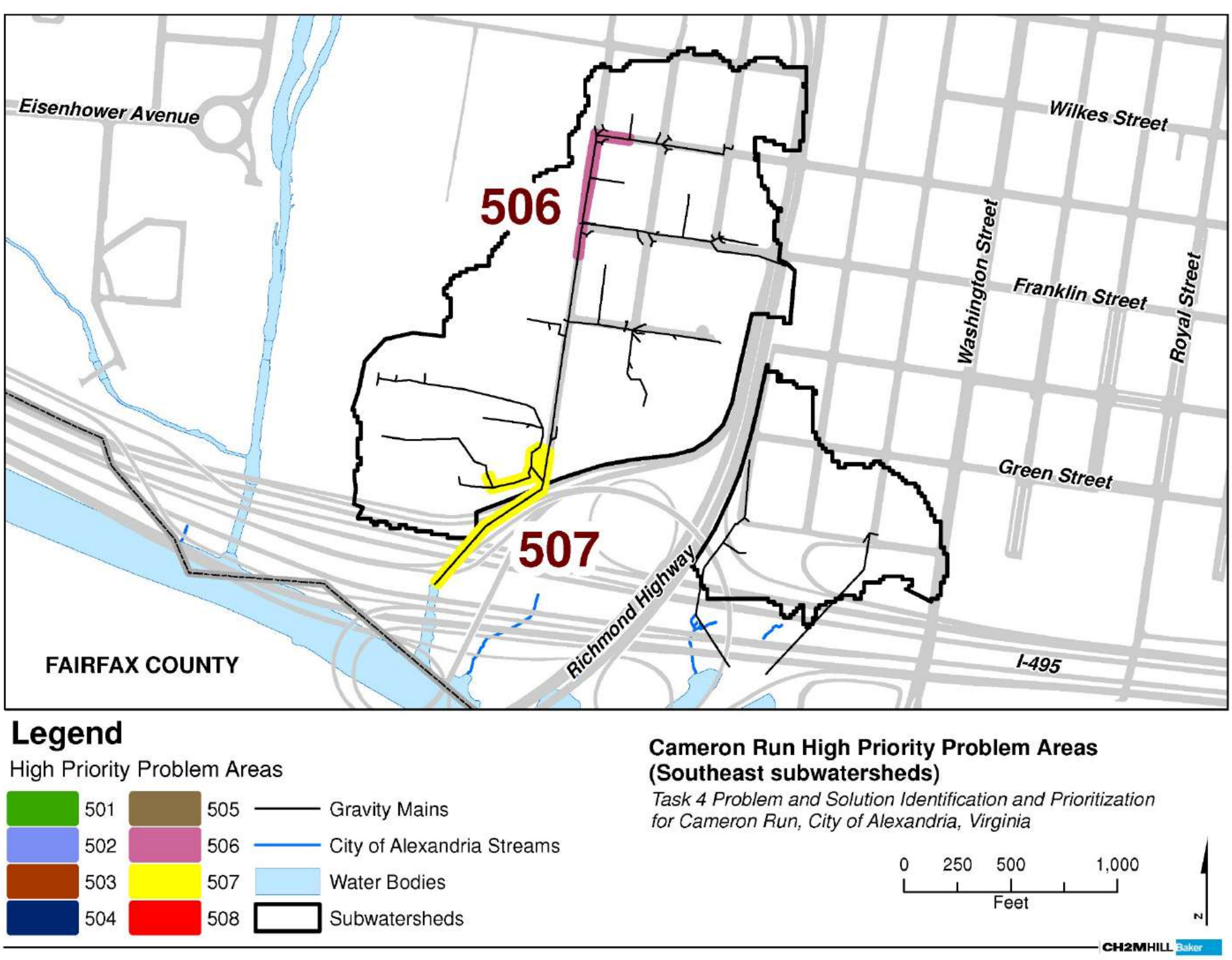
0 250 500 1,000
Feet

N

CH2MHILL Baker

FIGURE 3-2
Cameron Run High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run





SECTION 4

Solution Identification

A suite of solutions, including conveyance, storage, and GI projects, was developed for each problem area. The solution identification process resulted in 36 unique projects for the eight high-priority problem areas in the Cameron Run watershed. Because the solutions were focused on the high-priority problem areas, flooding outside those problem areas were not addressed by any of the alternatives. For example in Figure 3-2, there are pipe segments located east of Problem Area 506 near Franklin Street that experience some flooding but the Problem ID scores for this area are lower than the 35-point threshold because there is no critical infrastructure in the area, no historical record of flooding complaints from either the public or the staff, and there is good overland relief. As a result, solutions were not developed for this area. The following sections describes specific solutions developed for each problem area by project type, as well as the model results.

4.1 Conveyance Solutions

A conveyance solution was developed for each of the high-priority problem areas with the goal to remove hydraulic limitations in the drainage network by increasing the capacity of the pipes in high-priority problem areas. Because this was a high-level conceptual exercise rather than a design exercise, the pipe alignment and roughness were left unchanged, and capacity was increased solely by increasing the pipe size. In most cases, pipe shape was not altered except where sufficient capacity could not be achieved because of limited cover or where the existing pipe was a special shape, such as horizontal elliptical pipes. Where there was limited cover, circular pipes were changed to box culverts so that capacity could be increased without daylighting. Special pipe shapes were converted to equivalent-diameter circular pipes to simplify the model and calculations.

The conveyance capacity required was estimated using xpswmm. A hydraulic model was used to approximate the unconstrained peak flow in each pipe segment by upsizing pipes to 0.1-foot bgs to maximize diameter without daylighting the pipe, and by increasing the number of barrels by a factor of 2 across the board. The resulting unconstrained peak flow and Manning's equation were used to back-calculate the diameter required for the pipe to flow less than 80 percent full.

In the high-priority problem areas, the required diameter was compared to the existing diameter. Pipes that were smaller than the required pipe size calculated using the unconstrained peak flow were upsized and included in the conveyance project. Pipes that had sufficient capacity under existing conditions were left unchanged. Pipe size was not optimized during this exercise, and runs of pipes were not consistently sized. A summary of the length of pipe and range of pipe sizes included in each conveyance solution is included in Table 4-1. Appendix A contains a table documenting the existing and proposed diameter of each pipe segment.

TABLE 4-1
Summary of Conveyance Projects
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Project ID	Replacement Pipe Size Range and Project Description	Length (LF)
501	CONV-501	30-42 Inch Replacement Sewer Pipe Relief	501
502	CONV-502	18-24 Inch Replacement Sewer Pipe Relief	673
503	CONV-503	18-84 Inch Replacement Sewer Pipe Relief	600
504	CONV-504	42 Inch Replacement Sewer Pipe Relief	423
505	CONV-505	24-30 Inch Replacement Sewer Pipe Relief	412
506	CONV-506	42-54 Inch Replacement Sewer Pipe Relief	737
507	CONV-507	24-48 Inch Replacement Sewer Pipe Relief 4 ft by 7 ft Replacement Box Culvert Relief	543
508	CONV-508	102 Inch Replacement Sewer Pipe Relief	575

A map of the existing condition model results is provided on Figure 4-1 for reference, and a map of the conveyance solution model results is provided on Figure 4-2.

The conveyance solutions lessened or resolved some localized problems within the high-priority problem areas; however, some of the peak flow and volume is passed downstream creating new flooding and capacity limitations. Table 4-2 summarizes the model results for the existing condition model, which is the starting point for the conveyance solution model and the conveyance solutions. Side-by-side comparison shows that overall flooding is eliminated in about 5 percent of the system by length. The total duration of flooding decreases 30 percent and the total volume flooded is reduced by over 17 percent, indicating the severity of flooding is substantially reduced.

TABLE 4-2
Summary of Existing Condition and Conveyance Solution Models Results in Cameron Run
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Existing Condition Results				Conveyance Solution Results			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]
Sufficient Capacity	47,139	57	-	-	56,679	69	-	-
Surcharged[a]	13,653	17	453	-	10,839	13	417	-
Insufficient Freeboard	11,252	14	-	-	8,748	11	-	-
Flooded	10,042	12	73	2,117,542	5,820	7	57	1,811,126

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

Flooding outside of the high-priority problem areas was not addressed by the proposed solutions; therefore, a summary of the modeling results within the high-priority problem areas is provided in Table 4-3. A disadvantage of the conveyance solutions is that, while increasing pipe capacity reduces flooding in the problem area, it increases peak flows, which can create or increase flooding downstream. Peak flow was increased for five of the eight high-priority problem areas, ranging from a 28 percent increase in Problem Area 506 to a 50 percent increase in Problem Area 508. Comparably, flood volumes of conveyance solutions all decrease remarkably, with the minimum reduction as 63 percent of Problem Area 506; 76 percent of Problem Area 507; and 100 percent reduction of other problem areas.

TABLE 4-3
Conveyance Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

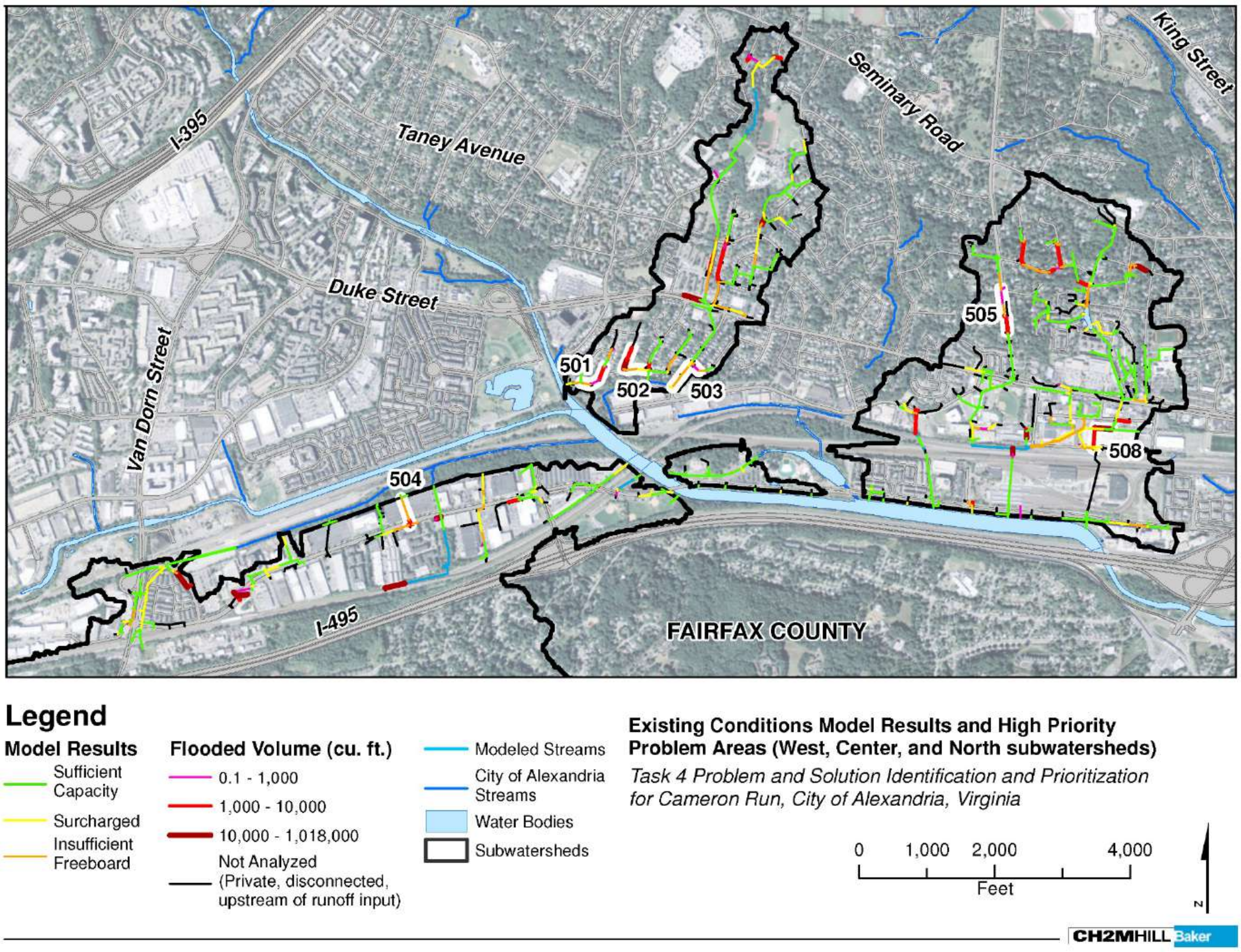
Problem Area ID	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
	Existing Conditions Model Results	Conveyance Solution Model Results	Percent Reduction	Existing Conditions Model Results	Conveyance Solution Model Results	Percent Increase
501	0.030	-	100	21.6	29.6	37
502	0.124	0.019	84	10.4	18.3	77
503	0.001	-	100	460.4	470.8	2
504	0.072	-	100	102.3	133.6	31
505	0.023	-	100	31.3	42.7	36
506	0.105	0.039	63	54.2	69.5	28

TABLE 4-3
Conveyance Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
	Existing Conditions Model Results	**Conveyance Solution Model Results**	**Percent Reduction**	**Existing Conditions Model Results**	**Conveyance Solution Model Results**	**Percent Increase**
507	0.672	0.160	76	105.7	156.2	48
508	1.813	0.006	100	253.5	379.3	50
		Average	**90**			**39**

The approach of sizing the conveyance projects based on the unconstrained peak flow allowed all conveyance projects to be run in a single iteration. Since stormwater gravity mains diameters were increased to convey the largest potential peak flow, the impact of increasing capacity upstream was incorporated into the sizing of any downstream conveyance solutions. However, evaluating all of the conveyance projects in a single model run has limitations. Because the problem areas are interconnected, modeling all solutions in a single run does not allow each solution to be viewed independently. Several problem areas are in proximity to one another; therefore, increasing the capacity at one location impacts the hydraulics in nearby problem areas, either by adding additional flow downstream or potentially increasing backwater for adjacent problem areas. For example, Problem Area 507 is located downstream of Problem Area 506; therefore, an increase of capacity within Problem Area 506 negatively affects the flooding condition at Problem Area 507 as shown in Table 4-3.

FIGURE 4-1
Existing Condition Model Results and High-Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



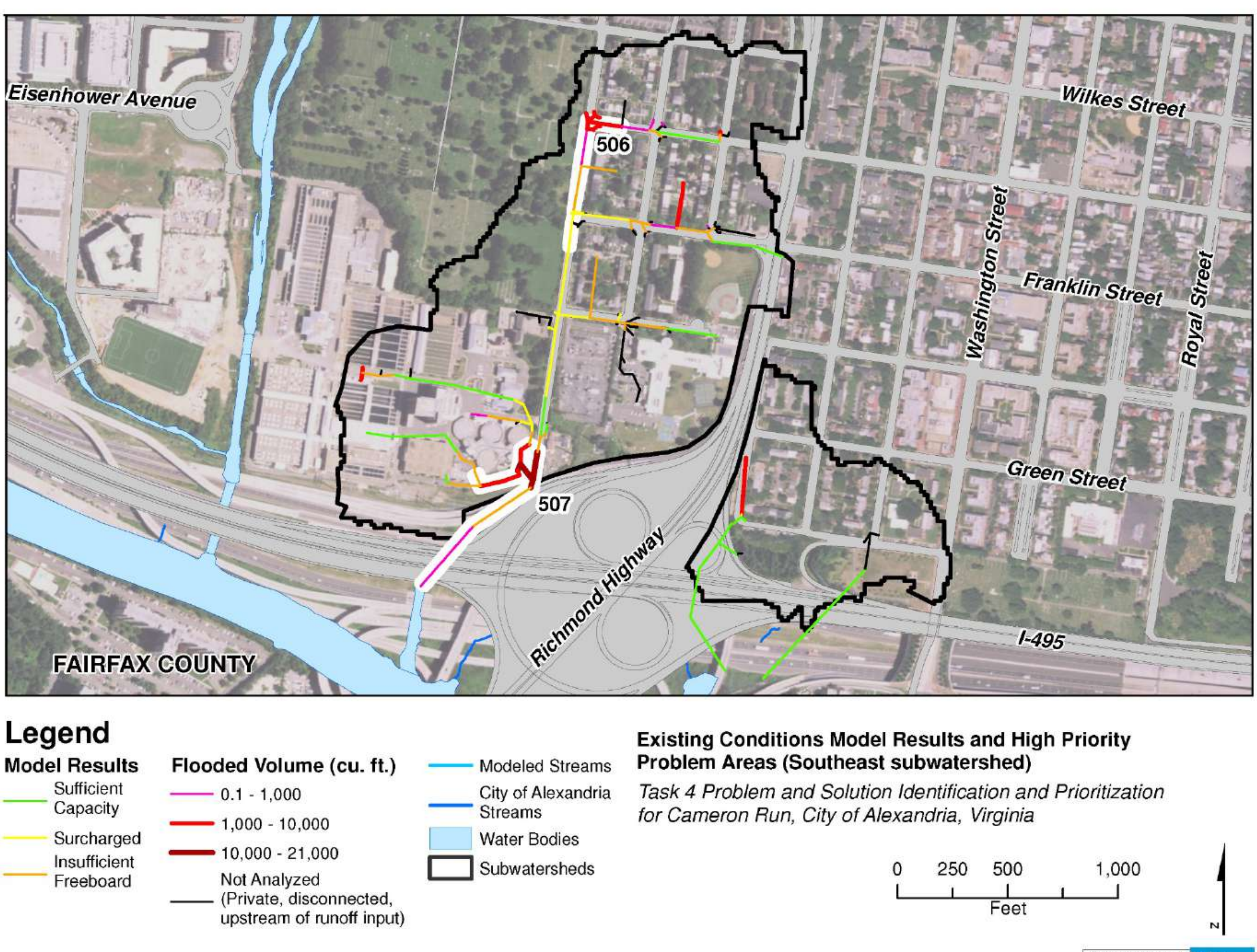
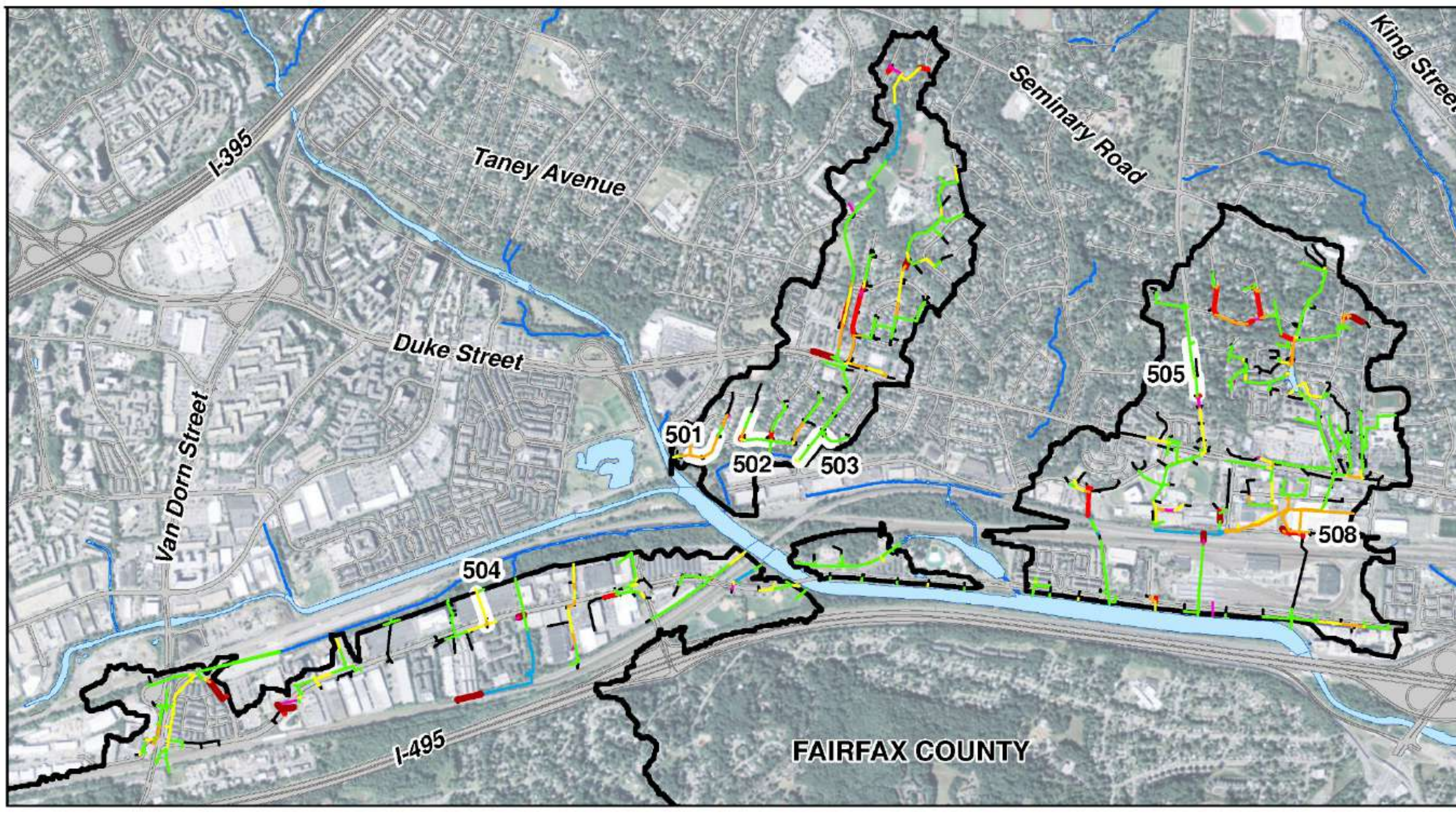


FIGURE 4-2
Conveyance Solution Model Results and High-Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

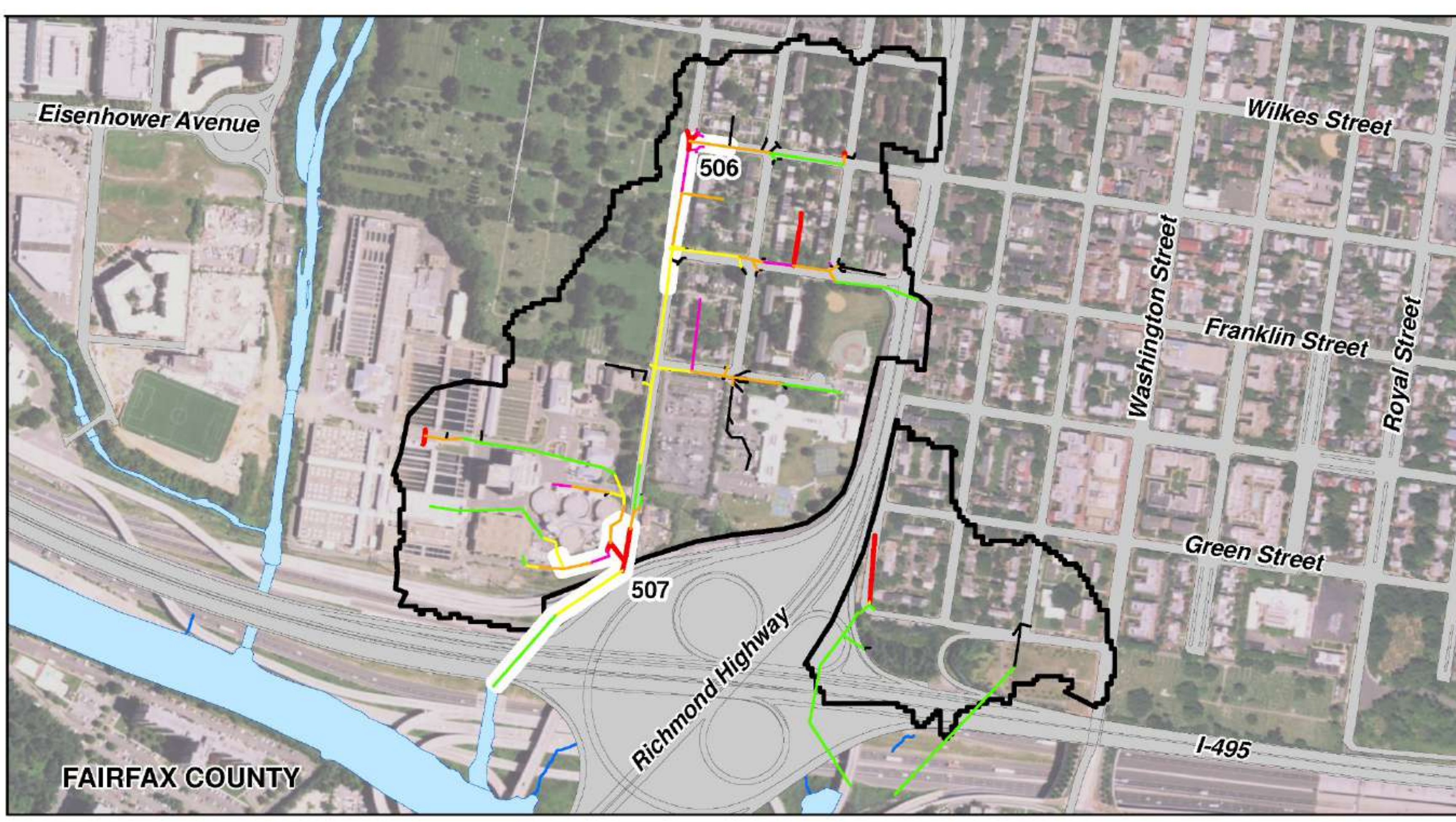
Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 1,017,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Conveyance Solutions Model Results and High Priority Problem Areas (West, Center, and North subwatersheds)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 1,000 2,000 4,000
Feet
N

CH2MHILL Baker



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 7,500
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Conveyance Solutions Results and High Priority Problem Areas (Southeast subwatershed)
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 250 500 1,000
Feet
N

CH2MHILL Baker

4.2 Storage Solutions

Conventional SWM solutions considered in this study include detention facilities and ordinance changes. Because of the challenges of translating ordinance changes into hydrologic and hydraulic parameters, only storage solutions were modeled in xpswmm. Ordinance changes were reviewed during the Hooffs Run Task solutions analysis and are summarized in *Task 4: Problem and Solution Identification and Prioritization for Hooffs Run, Alexandria, Virginia* (CH2M HILL, 2016).

The storage solutions goal was to add storage to the stormwater drainage network to decrease peak flow and volume during the modeled rainfall event. Because of the urban nature of the study area, it was assumed that to provide a sufficient storage volume, detention facilities would have to be below-grade vaults. Several constraints guided the siting of potential storage solutions, including the following:

- Depth of storage facility should not exceed 10 feet to minimize excavation costs
- Storage will be dewatered by gravity to a manhole less than 1,000 feet downstream to eliminate pumping costs
- Minimum storage depth should be 3 feet, measured from the storage inlet to the storage outlet
- Only surcharged flow will be sent to storage

The first step in developing storage solutions was to identify open space that may be available for subsurface storage vaults with preference for City-owned property. This primarily included parking lots, green space (for example, parks, school yards, playing fields, church yards), and grassed medians or boulevards. These storage areas were identified using aerial imagery and were deemed feasible using drainage network data (gravity main locations and inverts) and topographic data. Storage areas meeting the constraints described were identified for four of the eight high-priority problem areas; no storage opportunities were identified for Problem Areas 501, 502, 505, and 506. A map of these locations is provided on Figure 4-3. Table 4-4 summarizes the storage depth, area, and volume. More detailed maps of the storage solution locations are provided in Appendix B.

TABLE 4-4
Storage Solutions Summary
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Storage ID	Max Depth (ft)	Total Storage Area Available (ft^2)	Total Volume Available (ft^3)	Total Volume Required (ft^3)
503	STOR-503	7.6	7,441	56,624	12,248
504	STOR-504	6.0	4,911	29,565	20,042
507	STOR-507	3.6	12,655	45,305	45,305
508	STOR-508	4.2	24,436	102,631	102,631

No storage opportunities were identified for Problem Areas 501, 502, 505, and 506.

A map of the results of the storage solution model run is provided on Figure 4-4, and a summary of the results is provided in Table 4-5.

FIGURE 4-3
Storage Solution Locations and High-Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

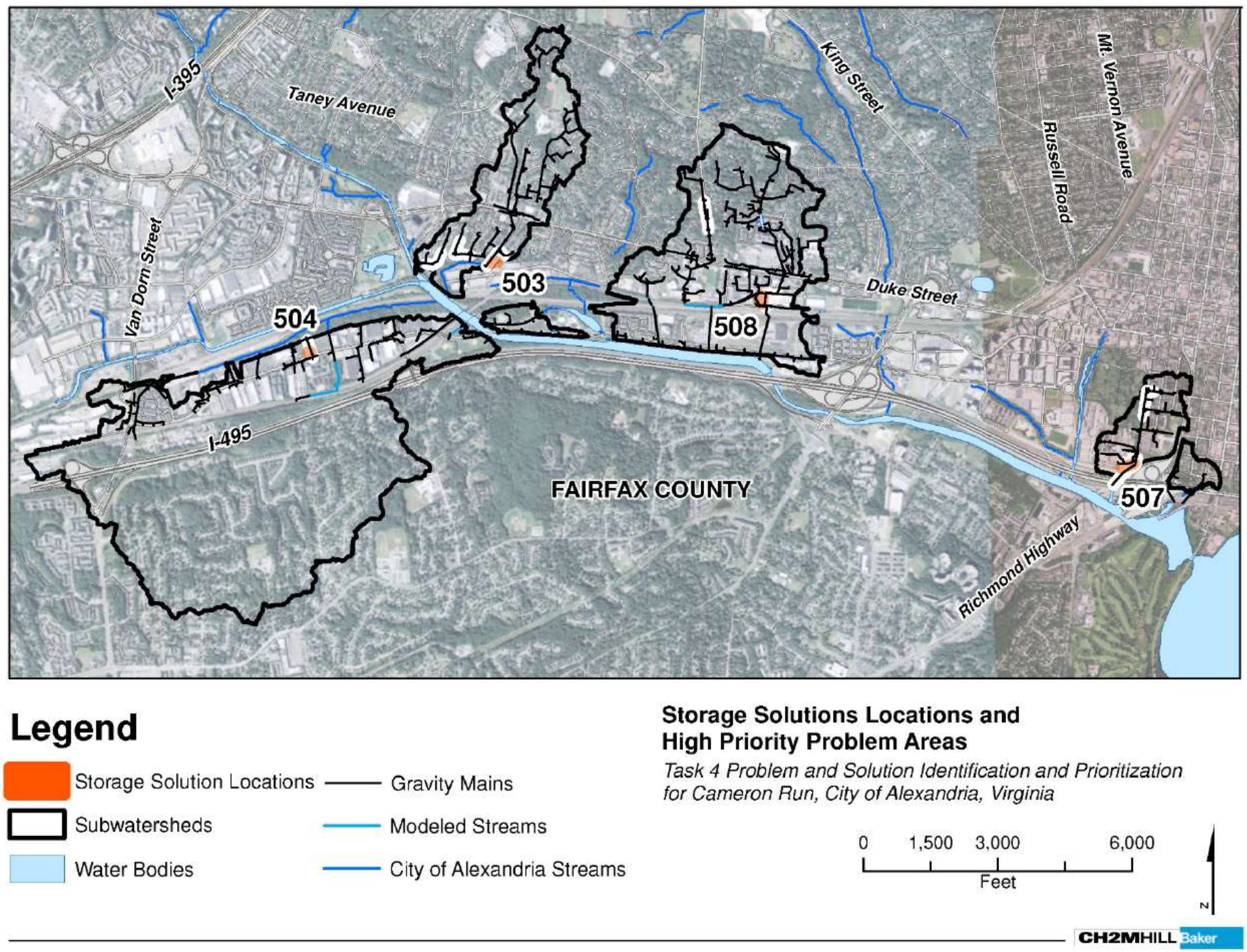
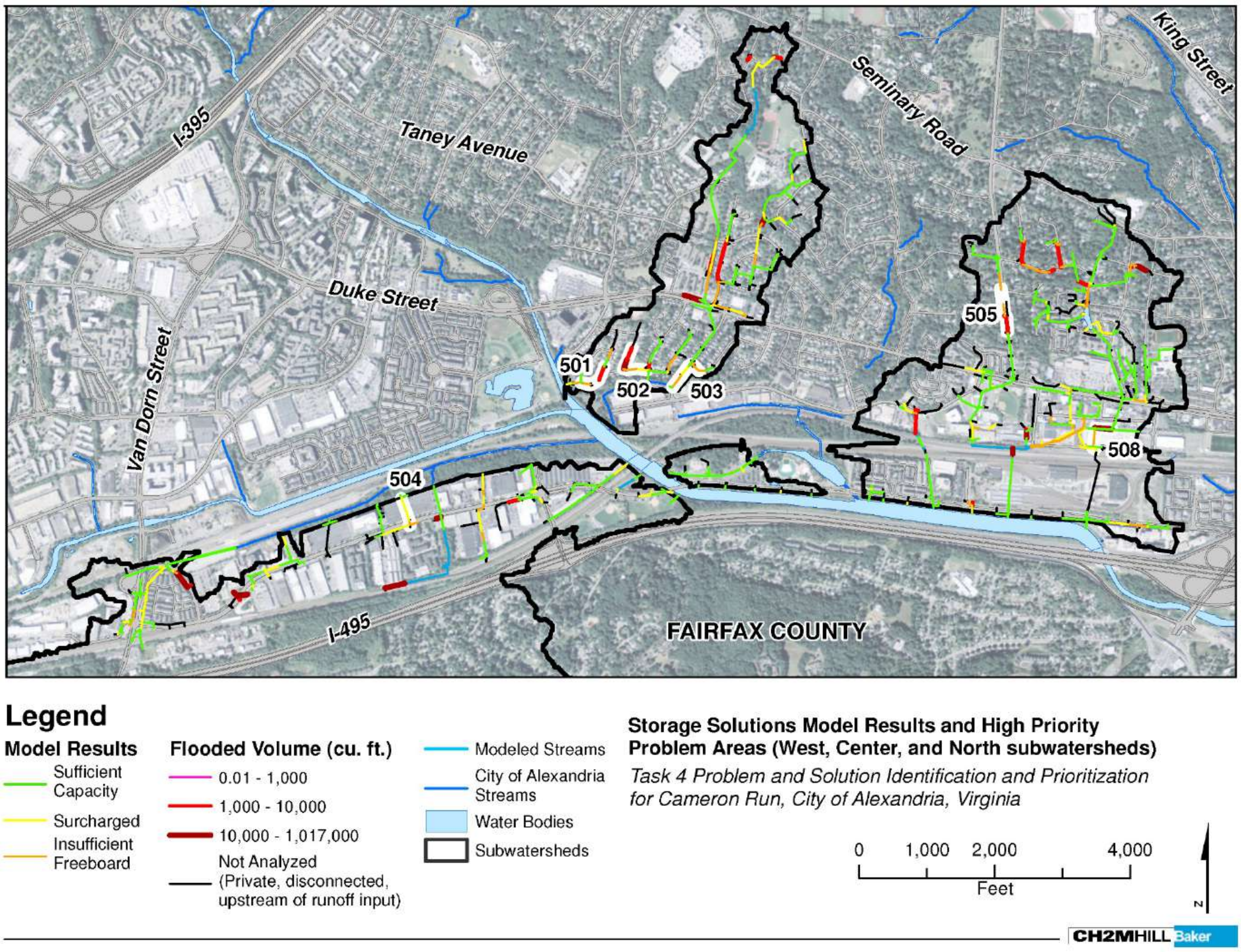


FIGURE 4-4
Storage Solutions Model Results and High-Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



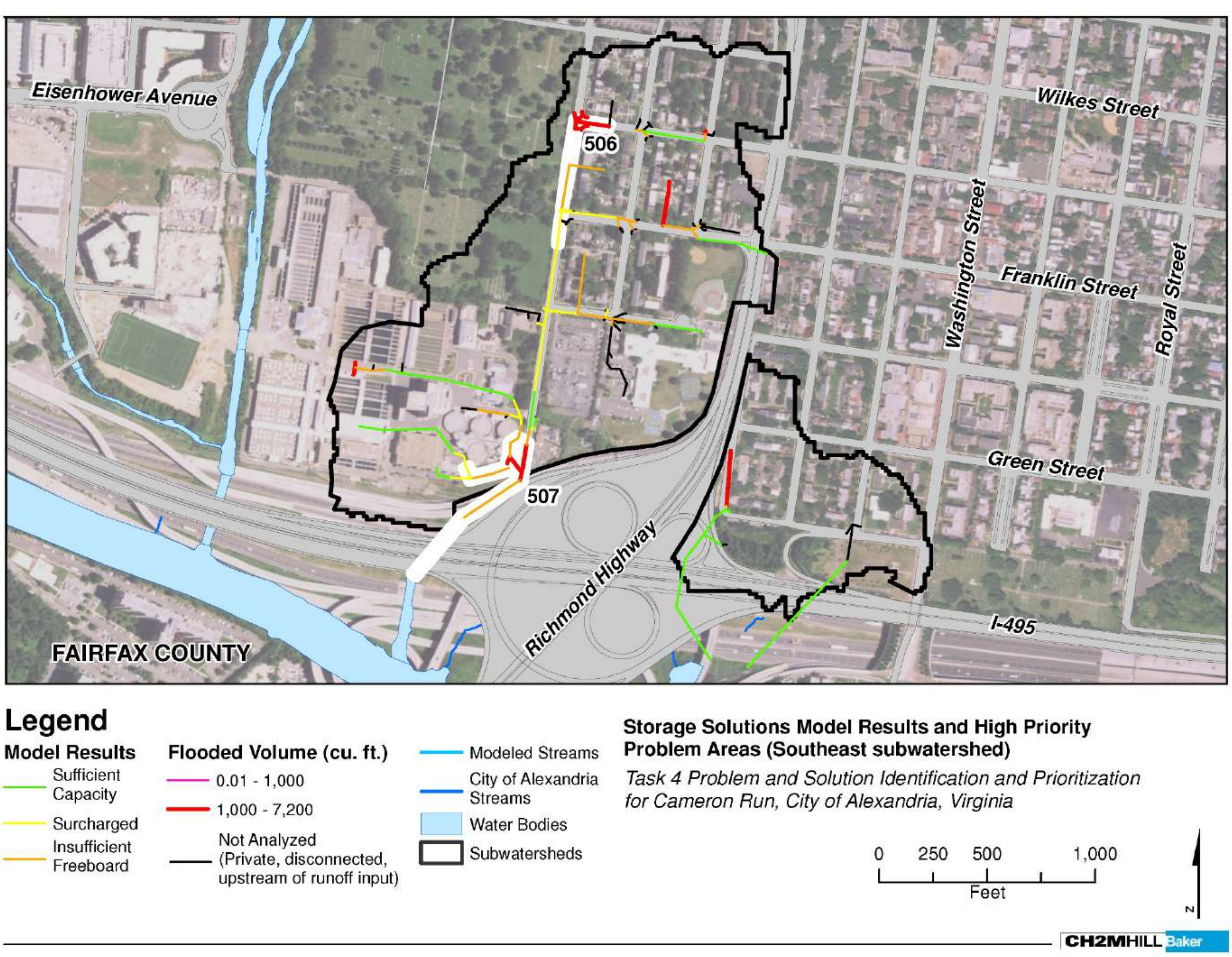


TABLE 4-5
Summary of Existing Condition and Storage Solution Models Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Existing Condition Model Results				Storage Solution Model Results			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft³)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft³)[b]
Sufficient Capacity	47,139	57	-	-	48,387	59	-	-
Surcharged[a]	13,653	17	453	-	13,755	17	442	-
Insufficient Freeboard	11,252	14	-	-	10,827	13	-	-
Flooded	10,042	12	73	2,117,542	9,117	11	63	1,827,020

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

Overall, the storage solutions implemented in half of the problem areas decrease the total volume of flooding in the watershed by more than 13 percent, and the duration of flooding is decreased by nearly 14 percent. Flooding is eliminated in about 1 percent of the system (by length), and a portion of these pipes contribute toward the increase in the length of surcharged pipes in the solution results. The total duration of surcharge in the system decreases by 11 hours; however, the length of surcharged pipe is increased by 102 feet. Flooding outside of the high-priority problem areas was not addressed by the proposed solutions; therefore, a summary of the modeling results within the high-priority problem areas is provided in Table 4-6. On average, the flood volume was reduced by 90 percent within the high-priority problem areas with installed storage solutions, and the peak flow was reduced by over 7 percent.

TABLE 4-6
Storage Solution Model Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Flood Volume (MG)			Peak Flow at Downstream End of Problem Area (cfs)		
Problem Area ID	Existing Condition Model Results	Storage Solution Model Results	Percent Reduction	Existing Condition Model Results	Storage Solution Model Results	Percent Reduction
503	0.0012	0.000	100	460.4	434.0	6
504	0.072	0.0043	94	102.3	91.6	11
507	0.672	0.124	82	105.7	98.8	7
508	1.813	0.279	85	253.5	236.2	7
		Average	**90**			**8**

No storage opportunities were identified for Problem Areas 501, 502, 505, and 506.

Evaluating all of the storage solutions in a single model is not limited by increases in downstream impacts as the conveyance solutions are. Instead, because of the increased storage capacity at upstream problem areas, the full peak flow may not reach downstream problem areas. In this case, the performance of a problem area may appear to be more favorable than if each problem area were modeled separately.

4.3 Green Infrastructure Solutions

The goal of GI solutions was to reduce the peak runoff rate and runoff volume directed to the storm drainage system by converting impervious surfaces to pervious surfaces. This is accomplished in the field by redirecting runoff from impervious surfaces to GI facilities that detain and infiltrate runoff during rainfall events. Three levels of GI (low, medium, and high) were evaluated in this analysis. In the model, GI was evaluated by reducing the impervious cover in model subcatchments by 10 percent, 30 percent, and 50 percent to represent the low, medium, and high levels of implementation, respectively.

Several GI technologies were considered feasible within the City including:

- **Bioretention and Planters** – planted depression or constructed box with vegetation that typically receives runoff from roadways or rooftop; includes vegetation and soil media over an underdrain and filtration fabric. The City does not typically encourage infiltration. Rain gardens, which typically do not have an underdrain, are not encouraged.
- **Cisterns** – a tank for storing water, typically connected to a roof drain, which can be either above or below ground. Water from a cistern is typically reused or slowly infiltrated into the soil rather than discharged to a storm sewer.
- **Green/Blue Roofs** - a roof of a building that is partially or completely covered with vegetation and a growing medium, planted over a waterproofing membrane (green roof) or a roof that is capable of storing and then slowly releasing rainwater (blue roof).
- **Porous Pavement** - paving surfaces designed to allow stormwater infiltration. This may or may not include an underground storage component.
- **Surface Storage** – retrofit of inlets and catch basins to include flow regulators on streets with standard curb and gutter system so that stormwater can be stored within the roadway and slowly released back into the storm sewer system.
- **Amended Soils** – altering soils to improve water retention, permeability, infiltration, drainage, aeration, and/or structure

These technologies were grouped into GI programs based on land uses where they could be applied. A program combines a set of technologies into an implementation strategy for different types of sites and land use categories. Programs being considered are as follows:

- **Green Streets and Alleys** – includes bioretention/planters and porous pavement combined along the public right-of-way between buildings and roadways. This can include parking lanes and curb cuts.
- **Green Roofs** – includes green/blue roofs, sometimes in combination with cisterns.
- **Green Schools** – use of school properties to implement one-to-many GI management strategies, including bioretention/planters, cisterns, green/blue roofs, and porous pavement.
- **Green Parking** – includes bioretention and planters and porous pavement in parking lots.
- **Green Buildings** – use of bioretention and planters, cisterns, and/or downspout disconnection on public or private buildings.
- **Blue Streets –** use short-term surface storage on streets with relatively flat slopes and standard curb and gutter systems.
- **Open Spaces** – use of open spaces to store and/or infiltrate stormwater with the use of a combination of detention, amended soils, bioretention and planters, and/or porous pavement. This may also include stream daylighting where appropriate.

Six GI concepts were developed for the Cameron Run watershed. These concepts are described in greater detail in Appendix C and demonstrate the applicability of GI technologies in the City.

A drainage area for each high-priority area was identified using the model's hydrologic subcatchments. Because the drainage area includes all model subcatchments upstream of the problem area, where there are problem areas upstream of one another (that is, Problem Area 506 is upstream of Problem Area 507), drainage areas overlap. A map of these drainage areas and problem area locations is provided on Figure 4-5. Table 4-7 summarizes the drainage area, existing impervious area, and impervious area for each level of GI implementation.

TABLE 4-7
Green Infrastructure Solutions Summary
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Drainage Area (acres)	Existing Impervious Area (acres)	GI Solution Impervious Area (acres)		
			Low Implementation	Medium Implementation	High Implementation
501	7.7	3.7	3.3	2.6	1.8
502	7.6	2.3	2.0	1.6	1.1
503	143.6	53.3	46.4	36.1	25.8
504	25.4	19.3	17.4	13.5	9.7
505	12.0	3.5	3.1	2.4	1.7
506	25.5	11.1	10.0	7.8	5.6
507	64.5	24.8	22.3	17.4	12.4
508	153.1	63.3	57.0	44.3	31.7

Maps of the results of the low, medium, and high GI solutions are provided on Figures 4-6 through 4-8, and a summary of the model results is provided in Table 4-8.

FIGURE 4-5
Green Infrastructure Drainage Areas and High Priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

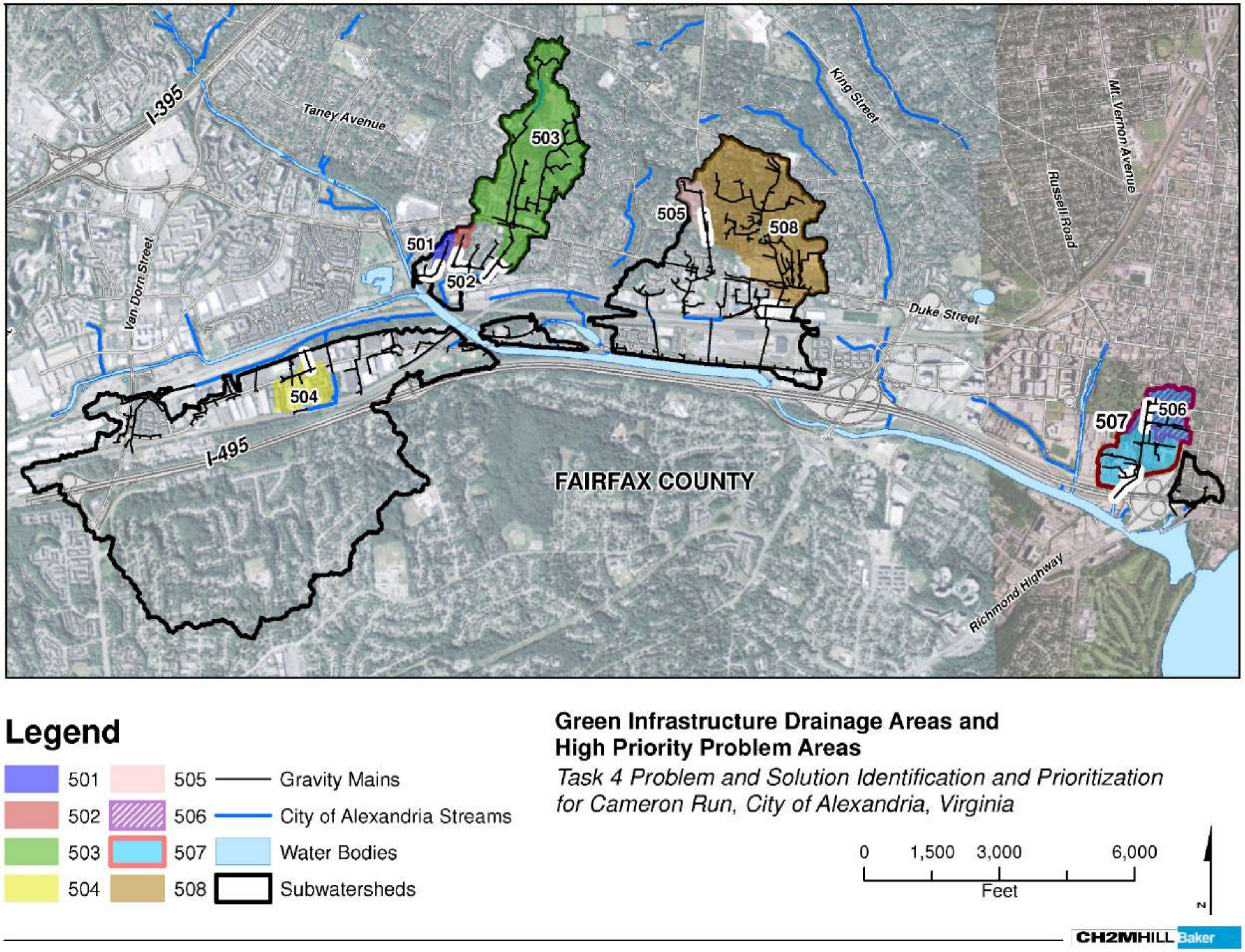
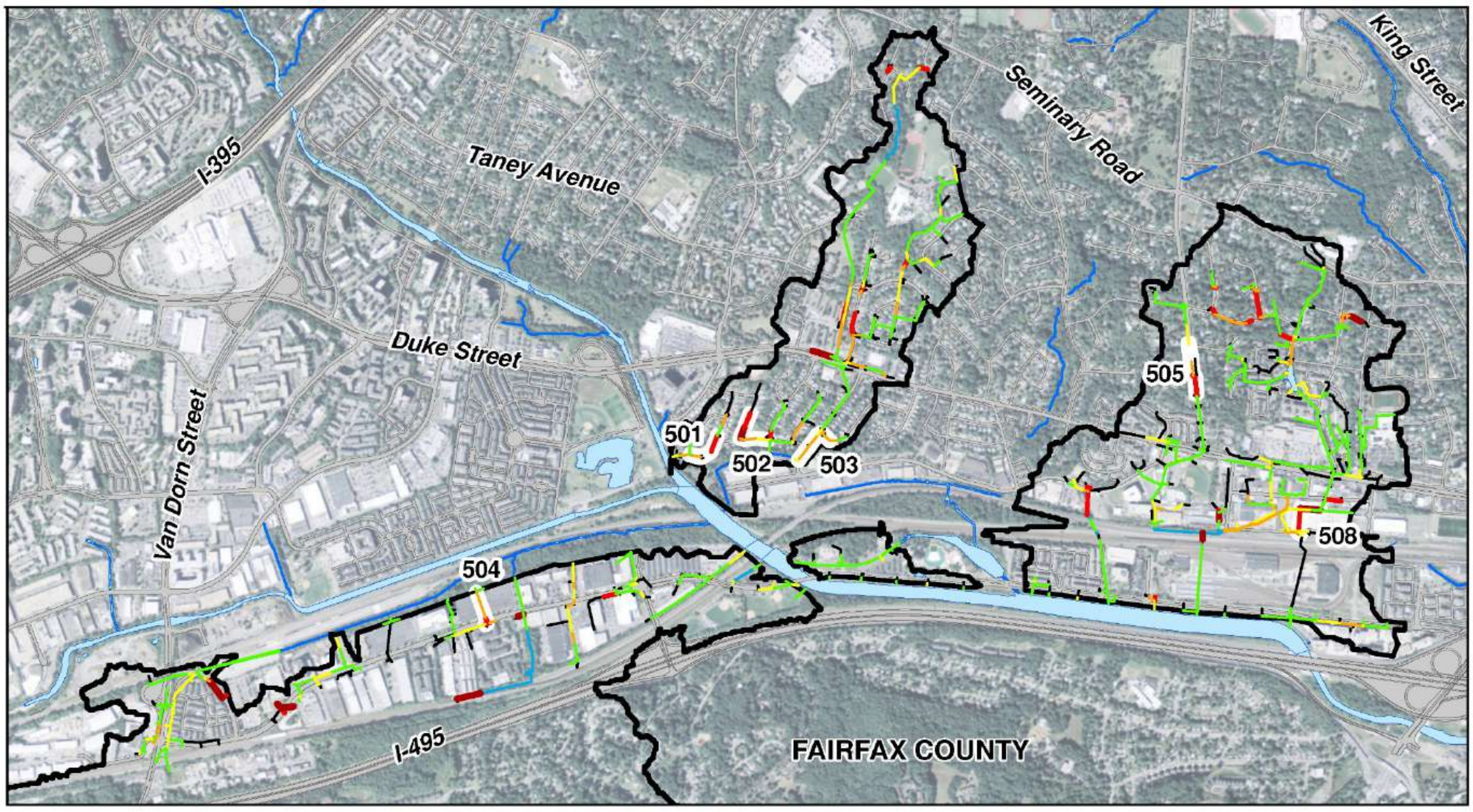


FIGURE 4-6
Low-implementation Green Infrastructure Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 1,017,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

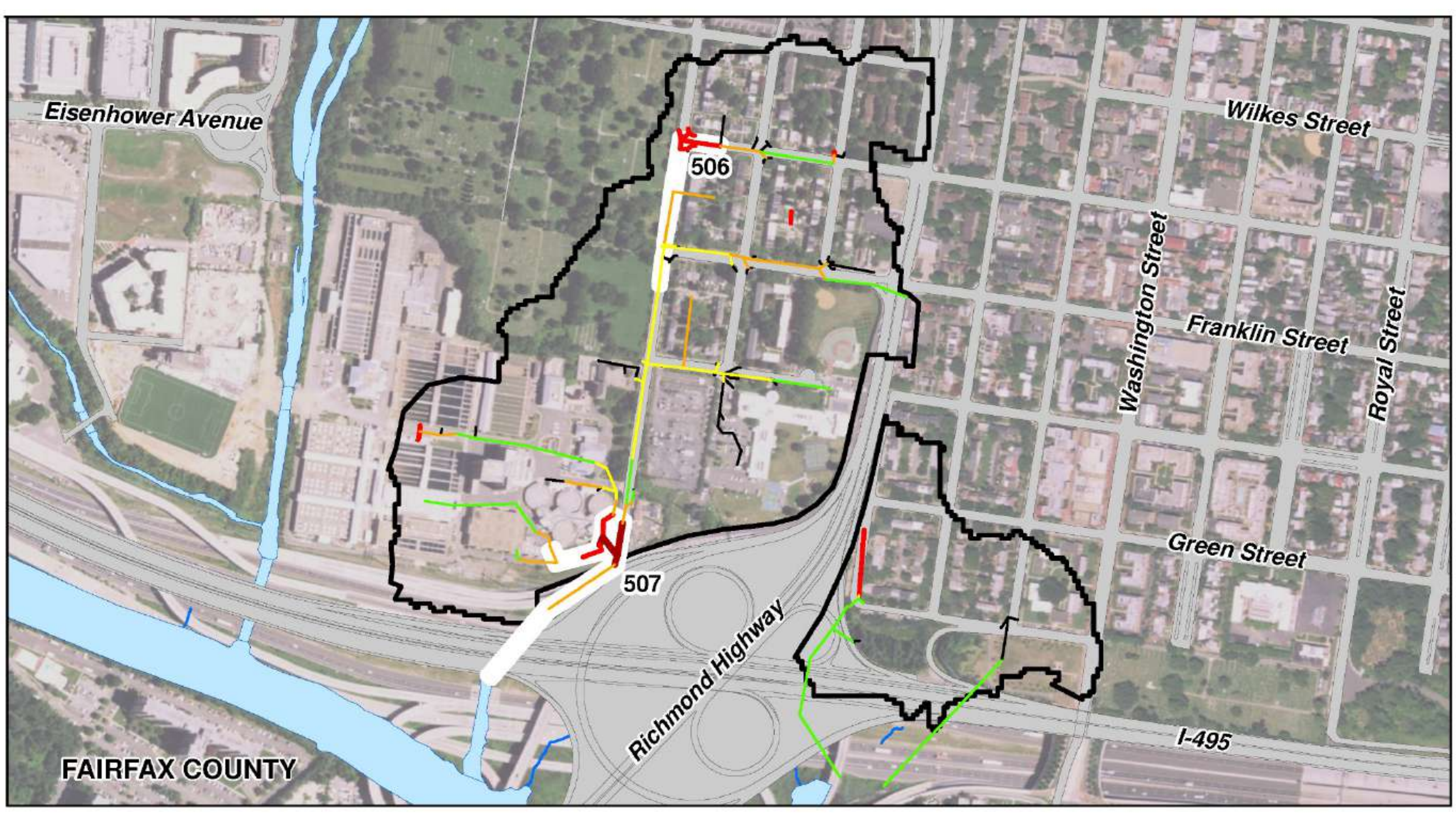
Low-Implementation Green Infrastructure Model Results and High Priority Problem Areas (West, Center, and North subwatersheds)

Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 1,000 2,000 4,000
Feet

N

CH2MHILL Baker



Legend

Model Results
- Sufficient Capacity
- Surcharged
- Insufficient Freeboard

Flooded Volume (cu. ft.)
- 0.01 - 1,000
- 1,000 - 10,000
- 10,000 - 20,000
- Not Analyzed (Private, disconnected, upstream of runoff input)

- Modeled Streams
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Low-Implementation Green Infrastructure Model Results and High Priority Problem Areas (Southeast subwatershed)

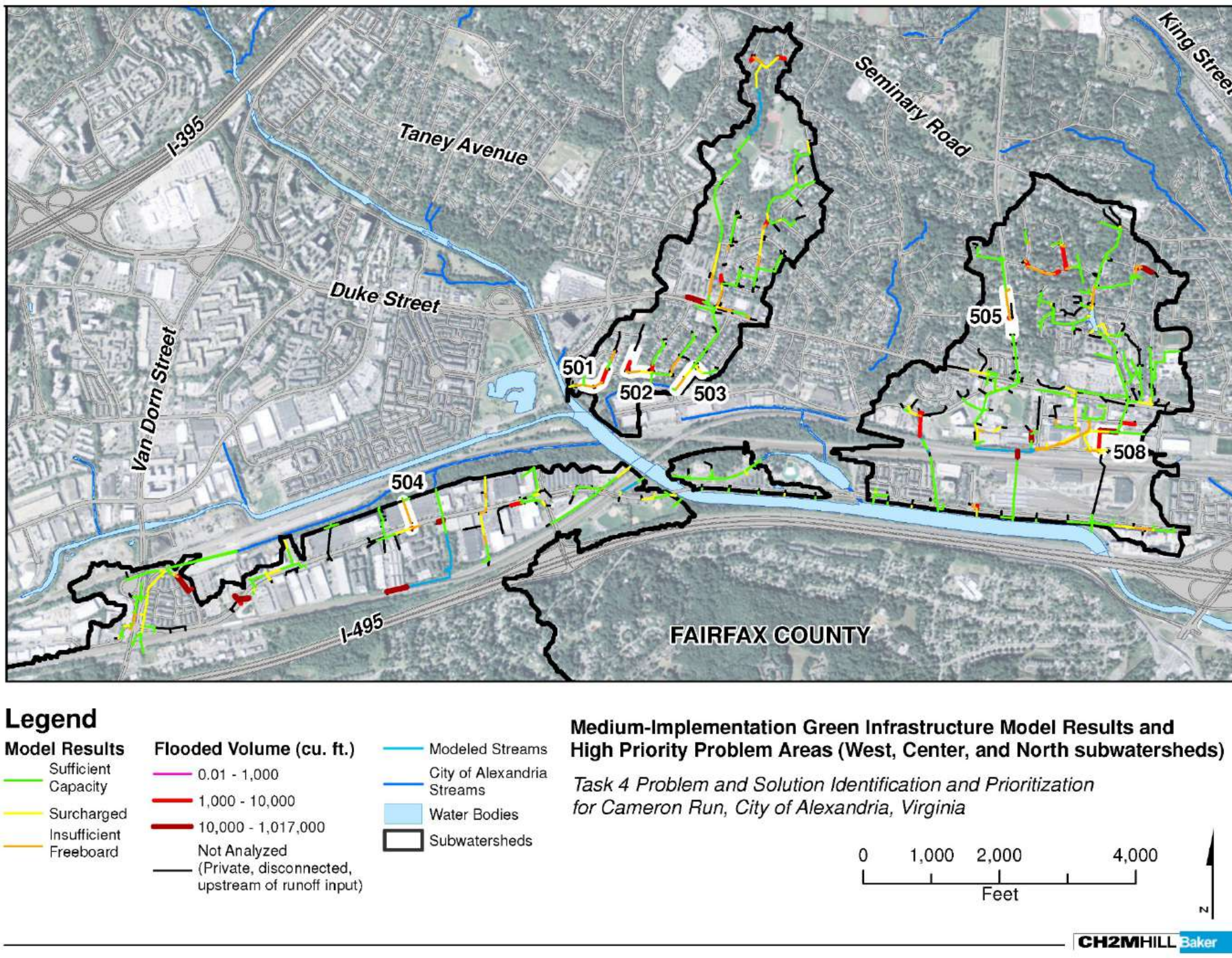
Task 4 Problem and Solution Identification and Prioritization for Cameron Run, City of Alexandria, Virginia

0 250 500 1,000
Feet

N

CH2MHILL Baker

FIGURE 4-7
Medium-implementation Green Infrastructure Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



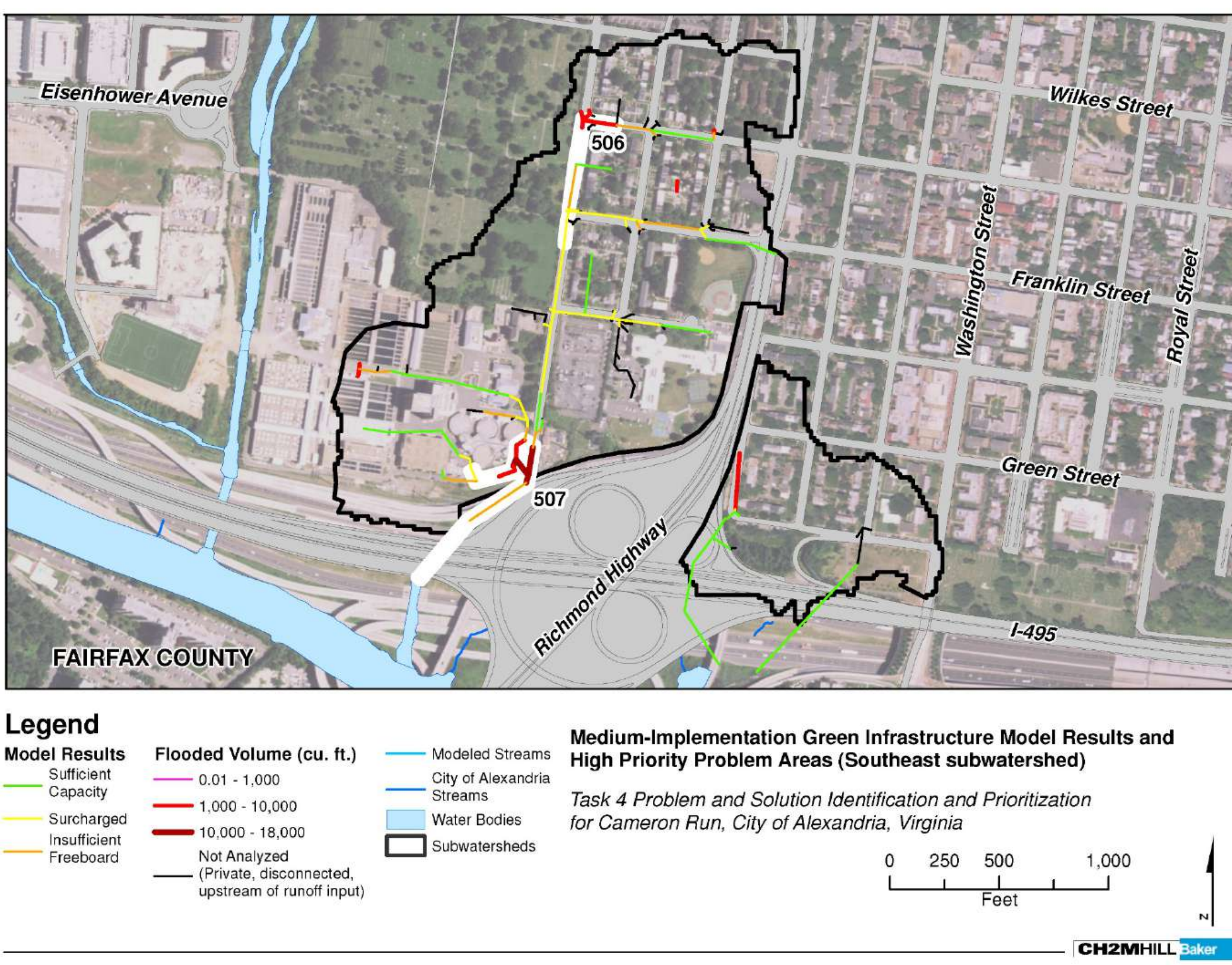
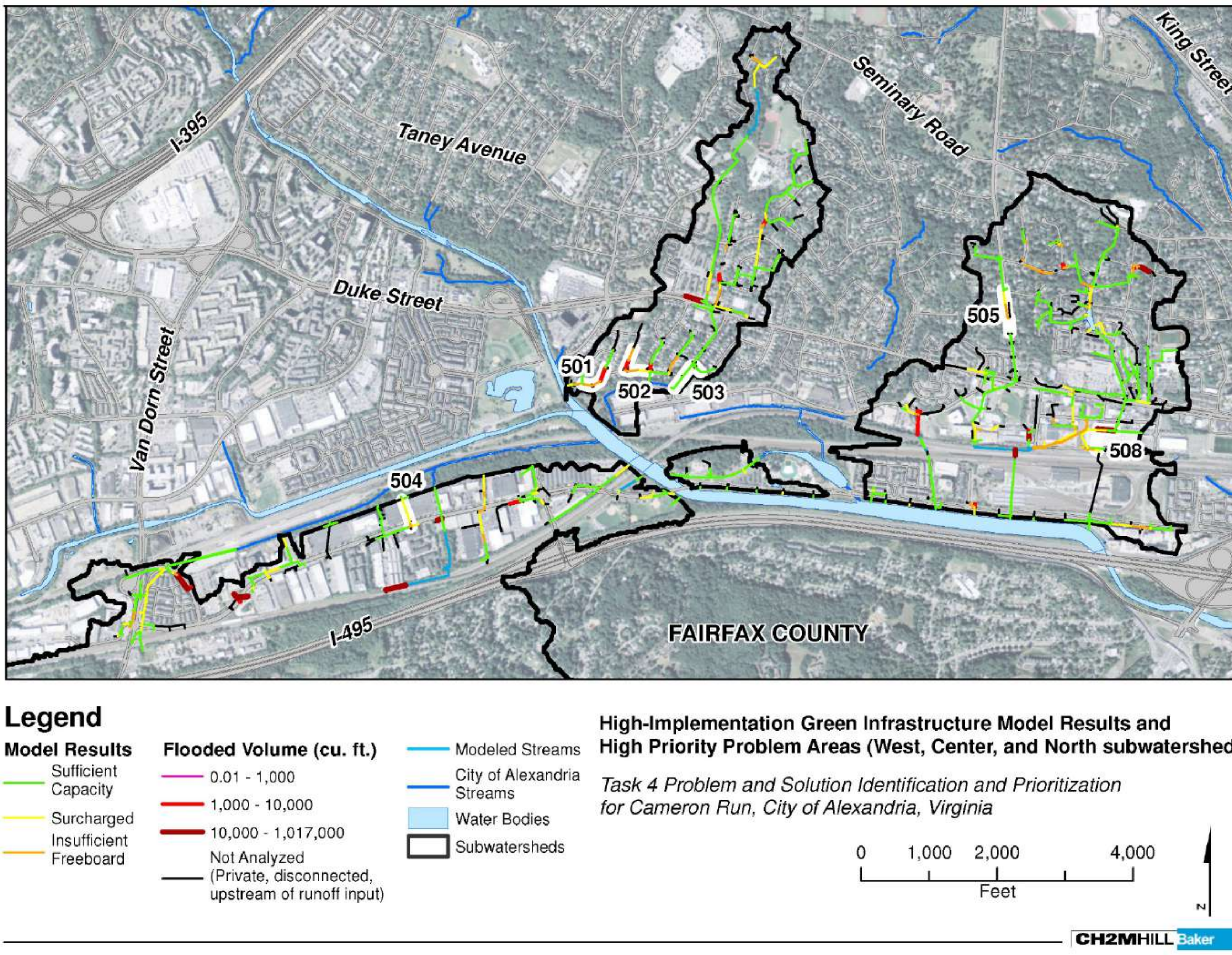


FIGURE 4-8
High-implementation Green Infrastructure Solution Model Results and High-priority Problem Areas
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



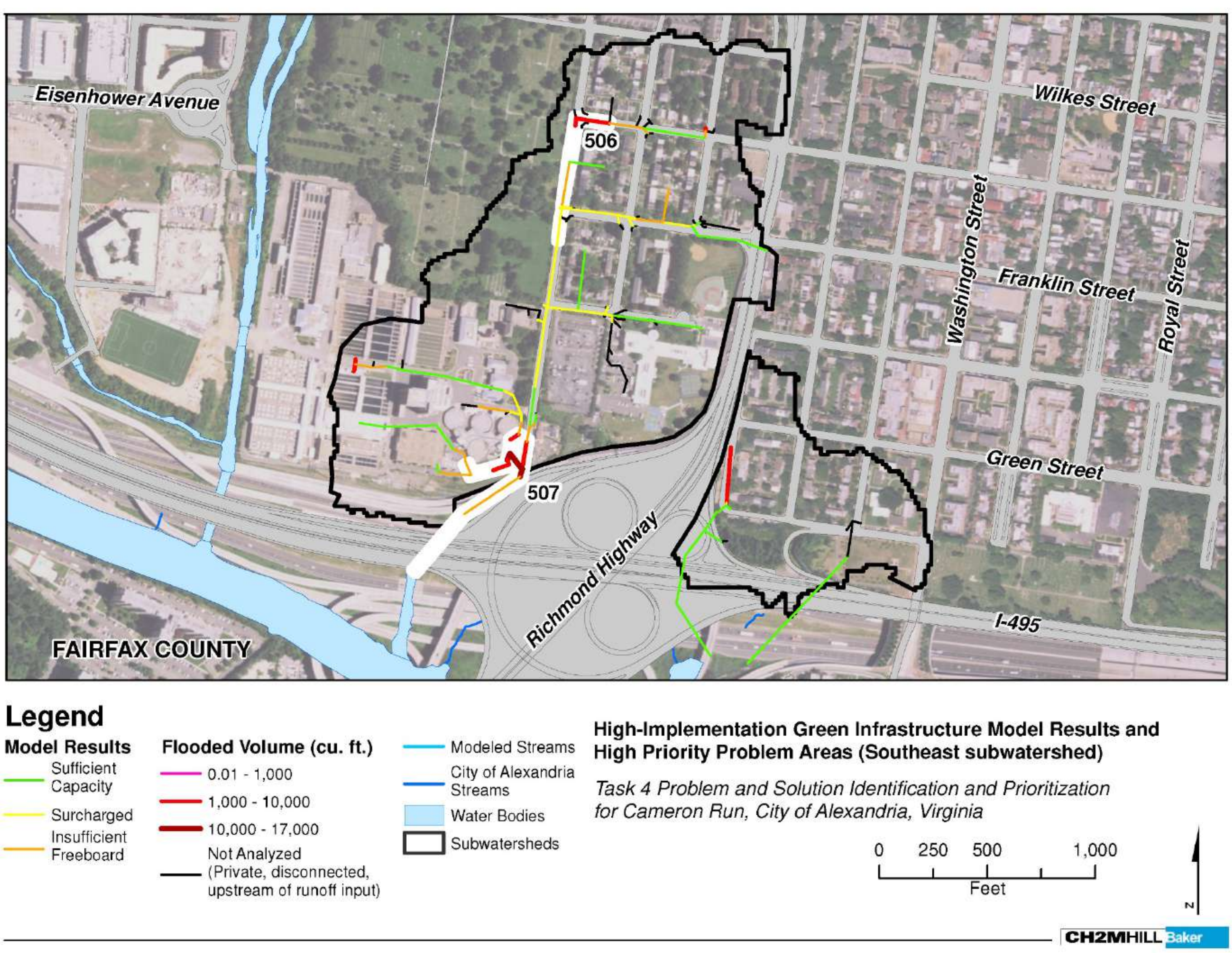


TABLE 4-8
Summary of Existing Condition and Green Infrastructure Implementation Models Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Existing Condition Results				Low GI Implementation Results				Medium GI Implementation Results				High GI Implementation Results			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]
Sufficient Capacity	47,139	57	-	-	47,980	59	-	-	49,737	61	-	-	52,419	64	-	-
Surcharged[a]	13,653	17	453	-	13,901	17	446	-	13,789	17	428	-	13,743	17	412	-
Insufficient Freeboard	11,252	14	-	-	10,909	13	-	-	10,210	12	-	-	8,219	10	-	-
Flooded	10,042	12	73	2,117,542	9,296	11	69	2,069,084	8,350	10	62	1,971,031	7,706	9	56	1,876,256

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

Overall, model results indicate that GI is effective at reducing flood volumes and durations. On the low end, a 10 percent impervious reduction by low GI implementation reduces length of flooding in the network by about 1 percent and reduces the overall flood volume by about 2 percent. The duration of flooding is also reduced slightly compared to the existing condition model results. On the high end, a 50-percent reduction in impervious area reduces length of flooding in the network by about 3 percent and reduces total flood volume by about 11 percent.

Flooding outside of the high-priority problem areas was not addressed by the proposed solutions; therefore, results within each high-priority problem area are shown in Tables 4-9 and 4-10. On average, the flood volume was reduced by about 25 percent in high-priority problem areas by the low GI implementation, nearly 47 percent by the medium GI implementation, and approximately 66 percent by the high GI implementation. Peak flow results were less dramatic, with the low GI implementation reducing peak flow by about 0.6 percent, medium GI implementation reducing peak flow by about 2.0 percent, and high GI implementation reducing peak flow by 4.3 percent.

TABLE 4-9
Green Infrastructure Solutions Flood Volume Models Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Existing Condition Flood Volume (MG)	Low GI Implementation		Medium GI Implementation		High GI Implementation	
		Solution Flood Volume (MG)	Percent Reduction	Solution Flood Volume (MG)	Percent Reduction	Solution Flood Volume (MG)	Percent Reduction
501	0.030	0.0267	12	0.0217	28	0.011	64
502	0.124	0.109	12	0.081	35	0.059	53
503	0.0012	-	100	-	100	-	100
504	0.072	0.0565	21	0.0237	67	-	100
505	0.0234	0.0158	33	0.0041	82	-	100
506	0.105	0.096	8	0.078	25	0.058	44
507	0.672	0.637	5	0.566	16	0.490	27
508	1.813	1.689	7	1.411	22	1.096	40
		Average	**25**		**47**		**66**

TABLE 4-10
Green Infrastructure Solutions Peak Flow Models Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Existing Condition Peak Flow (cfs)	Low GI Implementation		Medium GI Implementation		High GI Implementation	
		Solution Peak Flow (cfs)	Percent Reduction	Solution Peak Flow (cfs)	Percent Reduction	Solution Peak Flow (cfs)	Percent Reduction
501	21.6	21.3	1.5	20.7	4.4	20.0	7.5
502	10.4	10.3	0.2	10.3	0.6	10.2	1.2
503	460.4	451.5	1.9	435.8	5.3	408.5	11.3
504	102.3	101.7	0.6	100.2	2.0	94.6	7.6
505	31.3	31.3	0.1	31.2	0.5	31.1	0.7
506	54.2	54.1	0.3	53.6	1.2	52.8	2.6

TABLE 4-10
Green Infrastructure Solutions Peak Flow Models Results by Problem Area
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Existing Condition Peak Flow (cfs)	Low GI Implementation		Medium GI Implementation		High GI Implementation	
		Solution Peak Flow (cfs)	Percent Reduction	Solution Peak Flow (cfs)	Percent Reduction	Solution Peak Flow (cfs)	Percent Reduction
507	105.7	105.4	0.2	104.8	0.8	104.1	1.5
508	253.5	252.9	0.2	251.4	0.8	249.3	1.7
		Average	**0.6**		**2.0**		**4.3**

SECTION 5

Alternatives Analysis and Prioritization

The alternatives analysis and prioritization goal was to evaluate the cost and performance of the various solution approaches and technologies and develop watershed-wide alternatives aimed at resolving capacity-related problems in the Cameron Run watershed. The solution identification process resulted in 36 unique projects for the eight high-priority problem areas. The alternatives analysis and prioritization was performed after completing the solution modeling for the high-priority problem areas. The following section describes the results of the alternatives analysis and prioritization.

5.1 Problem Area Benefit Analysis

The 36 solutions for the eight high-priority problem areas were scored for the eight solution evaluation criteria:

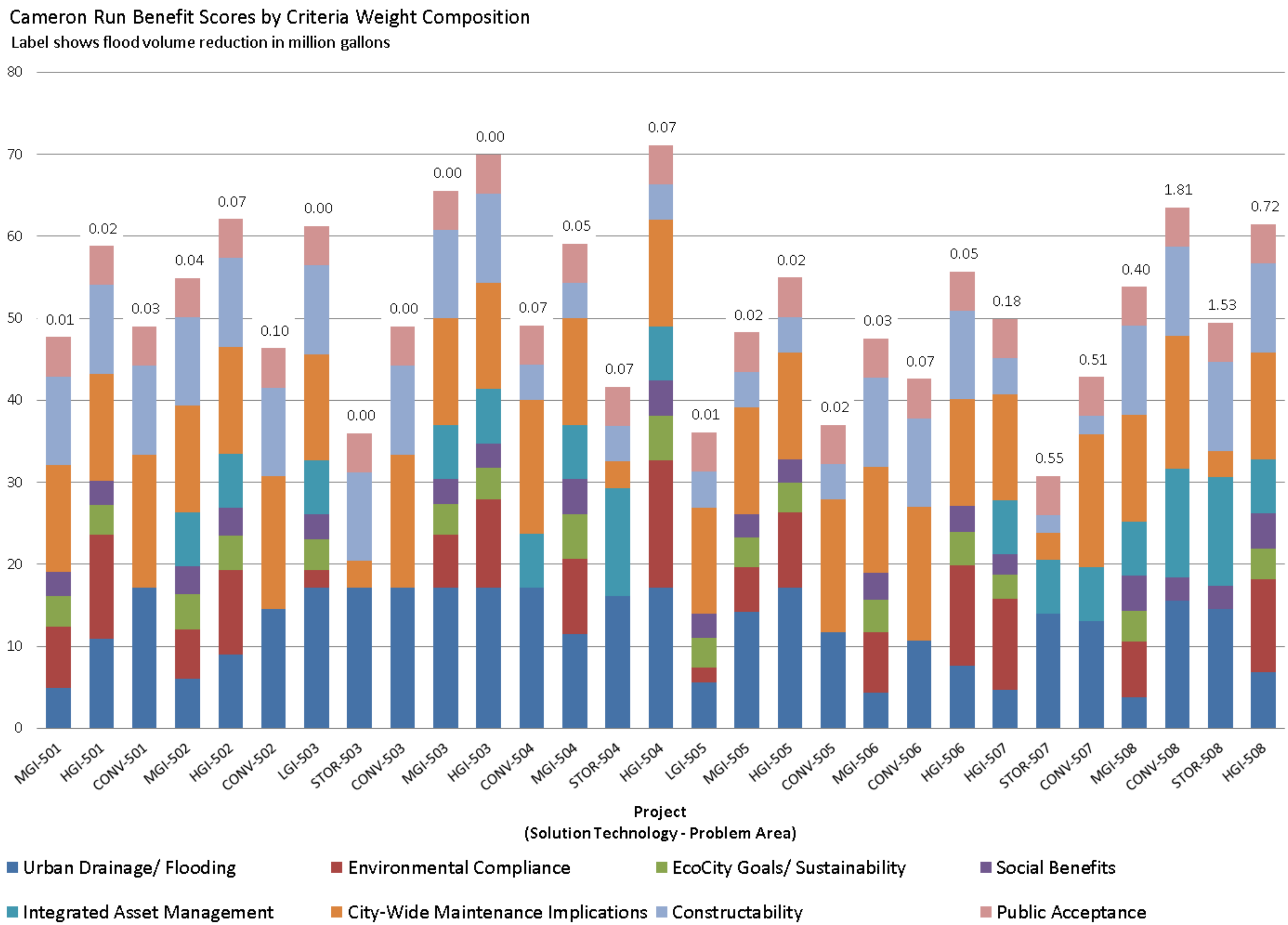
- Urban drainage/flooding
- Environmental compliance
- Eco-City goals/sustainability
- Social benefits
- Integrated asset management
- City-wide maintenance implications
- Constructability
- Public acceptability

After completing preliminary scoring of projects in Hooffs Run, City staff reviewed prioritization results to ensure the objectives of the analysis were being met. This review resulted in a minimum flood reduction threshold of 22 percent for all projects. If projects did not meet this minimum threshold, they were not included in the prioritization, though the scoring and costing data were maintained for documentation. Of the 36 solutions, seven did not meet the minimum flood reduction threshold, leaving 29 projects.

Figures 5-1 shows bar charts of the total benefit scores for these 29 projects. The horizontal axis has the project name, which is a combination of the problem area number and the technology/solution approach type. For example, CONV-1 is the conveyance solution for Problem Area 1; STOR-1 is the storage solution; and LGI-1, MGI-1, and HGI-1 are the low, medium, and high GI implementations, respectively. The charts show all solutions included in the prioritization (that is, all solutions providing at least 22 percent reductions in flooding) by problem area in ascending order from left to right.

A full table of the scoring and alternatives analysis results is included in Appendix D.

FIGURE 5-1
Total Benefit Score Chart for High-priority Problem Areas 501 through 508
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



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5.2 Problem Area Solution Costs

Planning-level capital costs (including construction, engineering, design, and contingency), were developed for each of the 29 solutions. The basis of the costs information for each technology is provided in Appendix E. The basic unit costs used for costing the various projects were the same across all City infrastructure projects. Three levels of GI implementation were evaluated for this project:

- High Implementation – Manage 50 percent of total impervious area in the watershed
- Medium Implementation – Manage 30 percent of total impervious area in the watershed
- Low Implementation – Manage 10 percent of total impervious area in the watershed

The unit cost of implementing GI at the various implementation levels is driven by the availability of GI opportunity areas. Since the GI opportunity areas varied across watersheds, the cost of implementation of the various levels of GI also varies across watersheds. Table 5-1 provides the construction cost assumptions for the low, medium, and high implementation levels of GI in Cameron Run watershed based on implementing GI across the whole watershed.

TABLE 5-1
Green Infrastructure Construction Costs
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

GI Level	Area Managed		Cost Per Acre Managed	Construction Cost
	Percentage	Acres		
Low GI	10	17.0	$39,595	$673,278
Medium GI	30	51.0	$55,735	$2,843,568
High GI	50	85.0	$71,875	$6,111,879

Table 5-2 provides the capital cost in millions of dollars for all 36 solutions. Projects that do not meet the minimum threshold for flood reduction are shown in ***bold italics***.

TABLE 5-2
Capital Costs for High-priority Problem Area Solutions
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

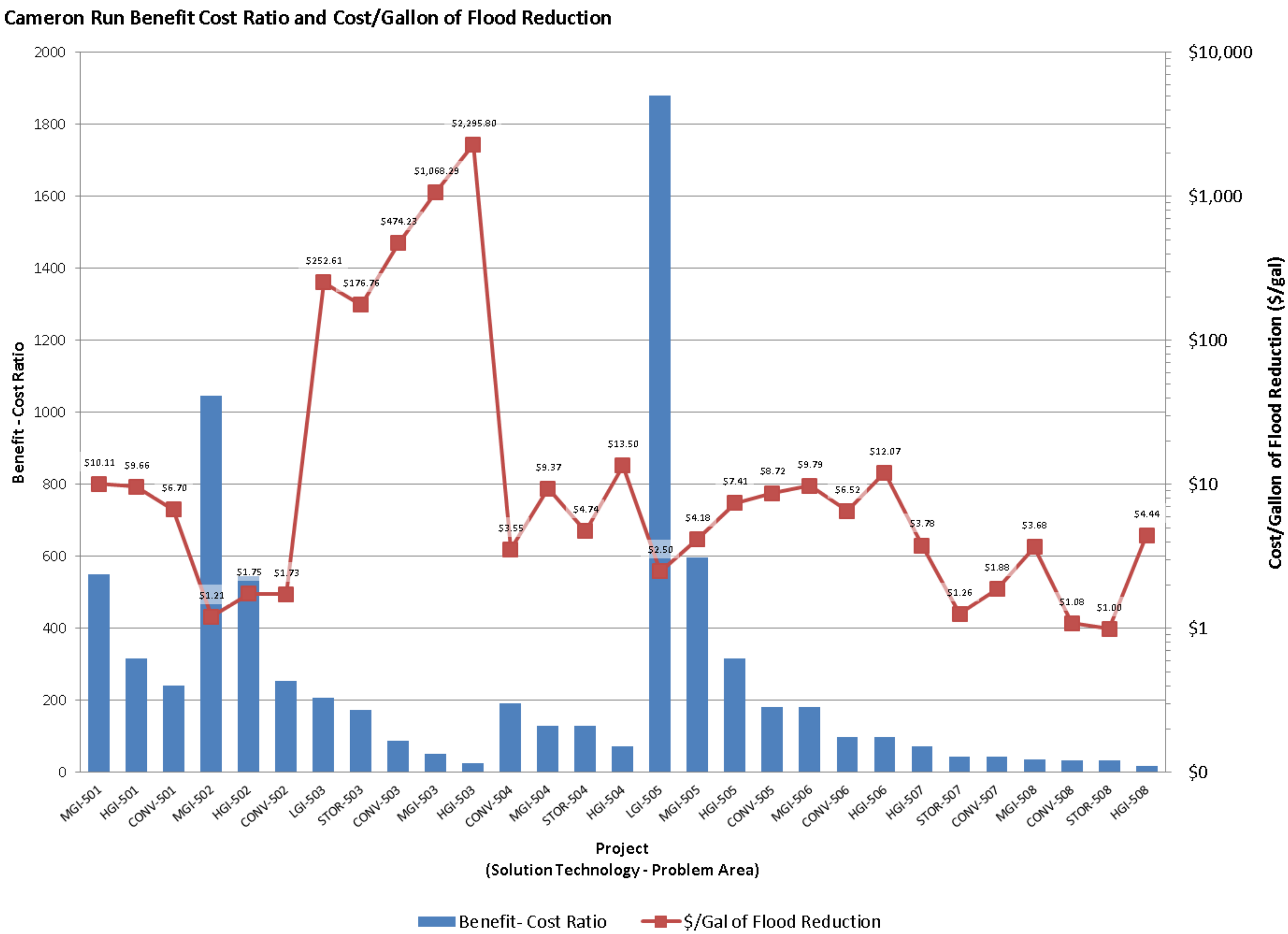
Problem Area	Conveyance ($M)	Storage ($M)	Low GI ($M)	Medium GI ($M)	High GI ($M)
501	$0.202	N/A	***$0.020***	$0.086	$0.185
502	$0. 181	N/A	***$0.012***	$0.052	$0.114
503	$0.554	$0.206	$0.295	$1.247	$2.681
504	$0.256	$0.320	***$0.107***	$0.452	$0.971
505	$0.204	N/A	$0.019	$0.081	$0.174
506	$0.429	N/A	***$0.062***	$0.261	$0.561
507	$0.961	$0.690	***$0.075***	***$0.319***	$0.687
508	$1.960	$1.529	***$0.351***	$1.481	$3.184

Notes:
Costs shown in ***bold italics*** are for projects that do not meet the 22 percent minimum flood reduction threshold set by the City.

5.3 Problem Area Benefit/Cost Results

The benefit/cost score is the ratio of the total benefit divided by the total capital cost in millions of dollars. This metric indicates the cost efficiency of a project and can help direct resources to the projects that will provide the greatest benefit for the lowest cost. Benefit/cost results are presented in Figure 5-2. The charts show only projects meeting the 22 percent minimum flood reduction threshold and are presented by problem area in ascending order from left to right on the horizontal access.

FIGURE 5-2
Benefit/Cost Chart for High-priority Problem Areas 501 through 508
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



The benefit/cost score is shown as a bar chart in blue. Additionally, the cost per gallon of flood reduction is included as a line on a logarithmic scale. This metric provides an alternative cost-based method for ranking projects. It is important to remember that the best projects will have a high benefit/cost score but a low cost per gallon of flood reduction.

5.4 Watershed-wide Alternatives

Three watershed-wide alternatives were developed for Cameron Run. Each watershed-wide alternative was aimed at resolving capacity-related issues while also meeting a second goal, which included maximizing cost-efficiency, benefit/cost, or targeting the highest-priority problems. The three alternatives examined include:

- Alternative 1: Most cost-effective solution for each problem area (lowest dollar-per-gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to resolve the highest-priority problem areas

Projects were selected for each of the watershed-wide alternatives based on the five individual technology-specific modeling results (Conveyance, Storage, and Low GI, Medium GI, and High GI implementation). A new model including the selected projects was run for each alternative. Results for the watershed-wide model runs are presented in section 5.4.4 and 5.4.5.

5.4.1 Alternative 1: Cost Efficiency

The first alternative focused on providing the best cost efficiency in each problem area. After removing projects that did not meet the minimum flood reduction threshold of 22 percent, the remaining projects were ranked by cost-per-gallon of flood reduction within each problem area in ascending order. The highest-ranked project, which was the project with the lowest cost-per-gallon of flood reduction, was selected for each problem area. Table 5-3 shows the selected project for each problem area. This alternative consisted primarily of conveyance and storage solutions with a couple GI projects. Model results are summarized in Table 5-7 and presented on Figures 5-3A and 3B.

The model results of this alternative show that flooding was decreased in all the Problem Areas. Conveyance solutions, while reducing flooding in the upstream problem area, increase peak flow out of the problem area by increasing capacity and can increase flows into a downstream problem area. In contrast, GI or storage implemented to resolve problems in an upstream problem area will also reduce flows in any downstream problem areas. If a conveyance solution is selected in a watershed-wide alternative instead of a GI or storage solution for an upstream problem area, the conveyance solution has a compounding impact on downstream problem areas. In this alternative, the selected solution for Problem Area 506 is conveyance, and so is Problem Area 507, which is downstream of 506. The increased peak flow experienced at Problem Area 507 because of conveyance projects upstream at 506 caused additional flooding within the problem areas, even while conveyance solutions were implemented.

TABLE 5-3
Selected Projects for Watershed-wide Alternative 1: Cost Efficiency
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit- Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
501	Conveyance	CONV-501	$0.202	242.1	0.030	100	$6.70
502	Medium GI	MGI-502	$0.052	1,046.5	0.043	35	$1.21
503	Storage	STOR-503	$0.206	174.5	0.001	100	$176.76
504	Conveyance	CONV-504	$0.256	192.1	0.072	100	$3.55
505	Low GI	LGI-505	$0.019	1,881.4	0.008	33	$2.50

TABLE 5-3
Selected Projects for Watershed-wide Alternative 1: Cost Efficiency
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit- Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
506	Conveyance	CONV-506	$0.429	99.4	0.066	63	$6.52
507	Conveyance	CONV-507	$0.961	44.6	0.511	76	$1.88
508	Storage	STOR-508	$1.529	32.3	1.534	85	$1.00
		Total	$3.65		2.266		

Note:
Results presented in this table are based on five separate technology-based model runs (Conveyance, Storage, and Low, Med, and High GI).
[a] Existing flood volume for Problem Areas 501 through 508 is 2.8 MG.

5.4.2 Alternative 2: Benefit/Cost

The second alternative focused on providing the best benefit/cost in each problem area. After removing projects that did not meet the minimum flood reduction threshold of 22 percent, the remaining projects were ranked by benefit/cost in descending order within each problem area. The highest-ranked project in each of the eight problem areas, which was the project with the highest benefit/cost score, was selected. Table 5-4 shows the selected project for each problem area. This alternative consisted of conveyance and GI projects. Model results are summarized in Table 5-7 and presented on Figures 5-4A and 4B.

TABLE 5-4
Selected Projects for Watershed-wide Alternative 2: Benefit/Cost
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit-Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
501	Medium GI	MGI-501	$0.086	551.4	0.009	28	$10.11
502	Medium GI	MGI-502	$0.052	1046.5	0.043	35	$1.21
503	Low GI	LGI-503	$0.295	207.7	0.001	100	$252.61
504	Conveyance	CONV-504	$0.256	192.1	0.072	100	$3.55
505	Low GI	LGI-505	$0.019	1,881.4	0.008	33	$2.50
506	Medium GI	MGI-506	$0.261	182.1	0.022	25	$9.79
507	Conveyance	CONV-507	$0.961	44.6	0.511	76	$1.88
508	MGI	MGI-508	$1.481	36.3	0.403	22	$3.68
		Total	**$3.84**		**1.202**		

Note:
Results presented in this table are based on five separate technology-based model runs (Conveyance, Storage, and Low, Med, and High GI).
[a] Existing flood volume for Problem Areas 501 through 508 is 2.8 MG.

5.4.3 Alternative 3: Highest-priority Problems

The third alternative focused on resolving the highest-priority problems by combining multiple solutions within a problem area. The minimum threshold of 22 percent flood reduction was removed because the goal was to eliminate as much flooding as possible from the problem area. In some cases, the combination of a storage or conveyance project that offered substantial flood reduction combined with a GI project could eliminate flooding within a problem area. The best combination of solutions in terms of cost efficiency, benefit/cost, and overall flood reduction were compiled to attempt to resolve the worst problem areas. Because eight projects were recommended in Alternatives 1 and 2 (one per project area), eight projects were selected for Alternative 3 to keep all three alternatives relatively consistent in scale. A total of eight projects were selected for Problem Areas 501, 502, 504, and 506 through 508. These were the problem areas which scored the highest when they were originally identified. Table 5-5 shows the selected project(s) for each problem area. Because the results are based on the five individual technology-based model runs, total percent flood reduction may sum to more than 100% where there are multiple projects in a single high-priority problem area. Model results are summarized in Table 5-7 and presented in Figures 5-5A and 5B.

TABLE 5-5
Selected Projects for Watershed-wide Alternative 3: Highest-priority Problems
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

Problem Area ID	Solution Technology	Project Name	Capital Cost ($M)	Benefit- Cost Ratio	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)
501	Conveyance	CONV-501	$0.202	242.1	0.030	100	$6.70
502	Conveyance	CONV--502	$0.181	255.4	0.105	84	$1.73
504	Conveyance	CONV-504	$0.256	192.1	0.072	100	$3.55
506	Conveyance	CONV-506	$0.429	99.4	0.066	63	$6.52
506	Medium GI	MGI-506	$0.261	182.1	0.027	25	$9.79
507	Conveyance	CONV-507	$0.961	44.6	0.511	76	$1.88
507	Medium GI	MGI-507	$0.319	136.0	0.106	16	$3.03
508	Conveyance	CONV-508	$1.960	32.4	1.807	100	$1.08
		Total	**$4.57**		**2.722**		

Note:
Results presented in this table are based on five separate technology-based model runs (Conveyance, Storage, and Low, Med, and High GI).
[a] Existing flood volume for Problem Areas 501 through 508 is 2.8 MG.

5.4.4 Modeling Results

Table 5-6 provides a summary of the hydraulic model results for the three watershed-wide alternatives. Alternative 3, which focuses on resolving the highest-priority problems, provides the greatest reduction of flooding in the system in terms of total length of pipe experiencing flooding, minimizes the duration of flooding, and minimizes the total volume of flooding in the system overall. Maps comparing the model results are presented on Figures 5-3 through 5-5.

Each of the alternatives analyzed is still leaving areas with flooding (as shown by red lines on the maps), largely because those areas are outside the boundaries of the “high-priority problem areas”. These areas were not addressed by solutions because they were either flooding at isolated structures, or did not score high based on the problem area scoring criteria.

TABLE 5-6
Summary of Watershed-wide Alternative Models Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Existing Condition Results				Alternative 1 Results Best Cost Efficiency				Alternative 2 Results Best Benefit/Cost Ratio				Alternative 3 Results Highest-priority Problems			
	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]	Conduit Length (LF)	Percent of Total Length (%)	Total Duration (hrs)	Total Volume (ft^3)[b]
Sufficient Capacity	47,139	57	-	-	48,741	59%	-	-	48,071	59%	-	-	48,287	59%	-	-
Surcharged[a]	13,653	17	453	-	14,130	17%	424	-	13,425	16%	420	-	13,768	17%	413	-
Insufficient Freeboard	11,252	14	-	-	10,759	13%	-	-	12,283	15%	-	-	12,252	15%	-	-
Flooded	10,042	12	73	2,117,542	8,456	10%	58	1,808,689	8,307	10%	57	1,929,693	7,779	10%	56	1,797,864

Notes:
Results presented for pipe segments are based on capacity at upstream end of pipe.
[a] Duration of surcharged flow includes time during which conduits are surcharged, have insufficient freeboard, or are flooded at upstream end only.
[b] Flooded volume includes volume flooded at upstream end of the conduit.

FIGURE 5-3A
Alternative 1: Best Cost-efficiency Model Results (West, Center, and North subwatersheds)
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

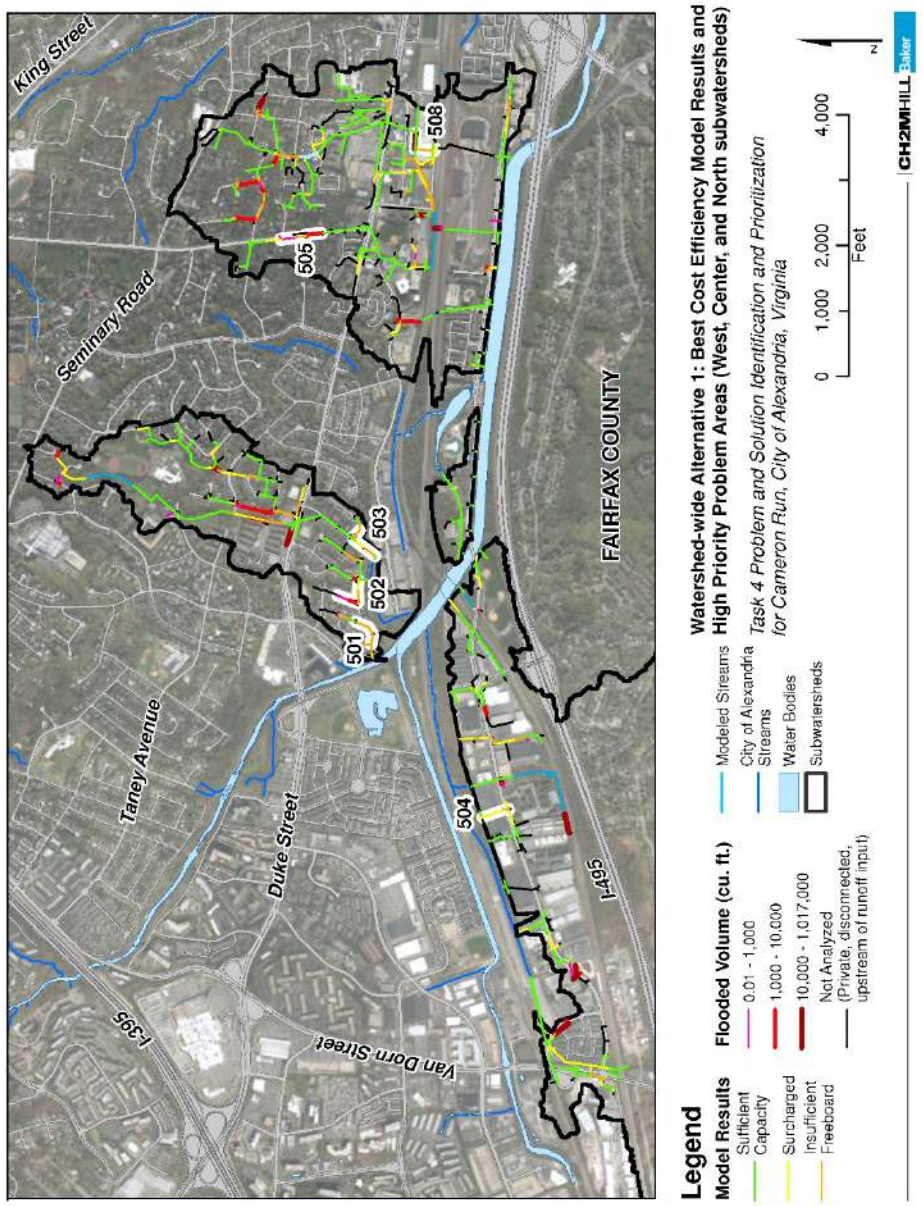


FIGURE 5-4A
Alternative 2: Best Benefit/Cost Ratio Model Results (West, Center, and North subwatersheds)
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

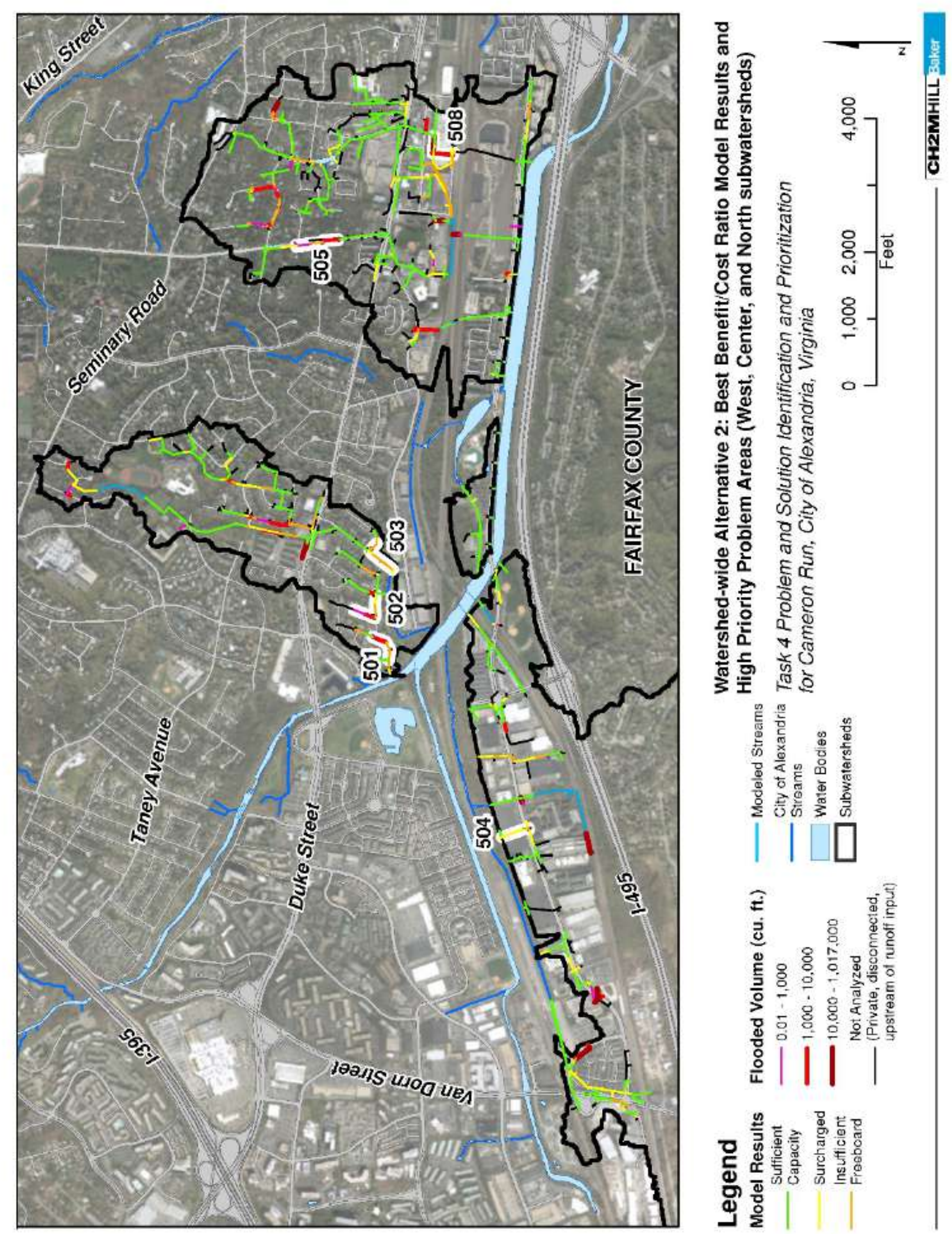


FIGURE 5-5A
Alternative 3: Highest-priority Problems Model Results (West, Center, and North subwatersheds)
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

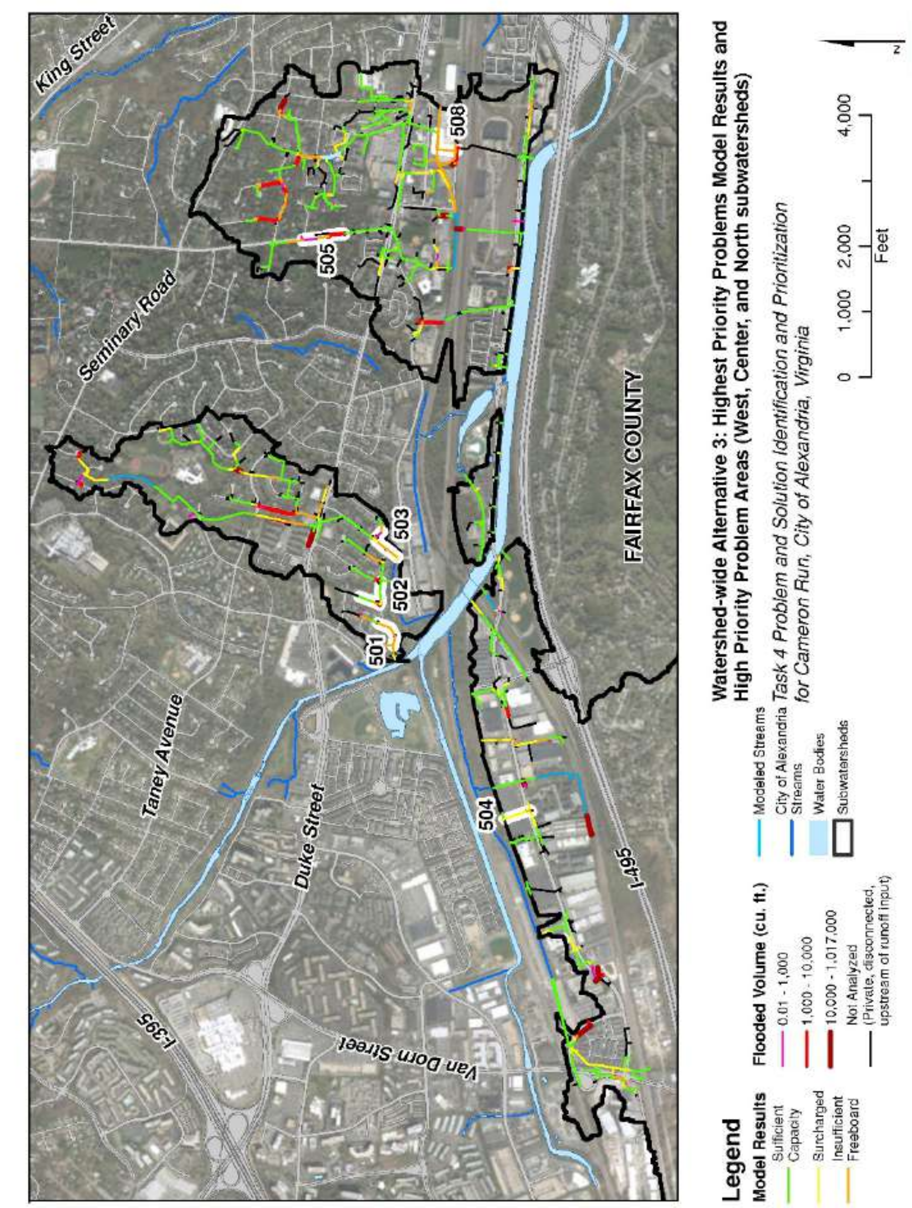


FIGURE 5-3B
Alternative 1: Cost-efficiency Model Results (Southeast subwatershed)
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

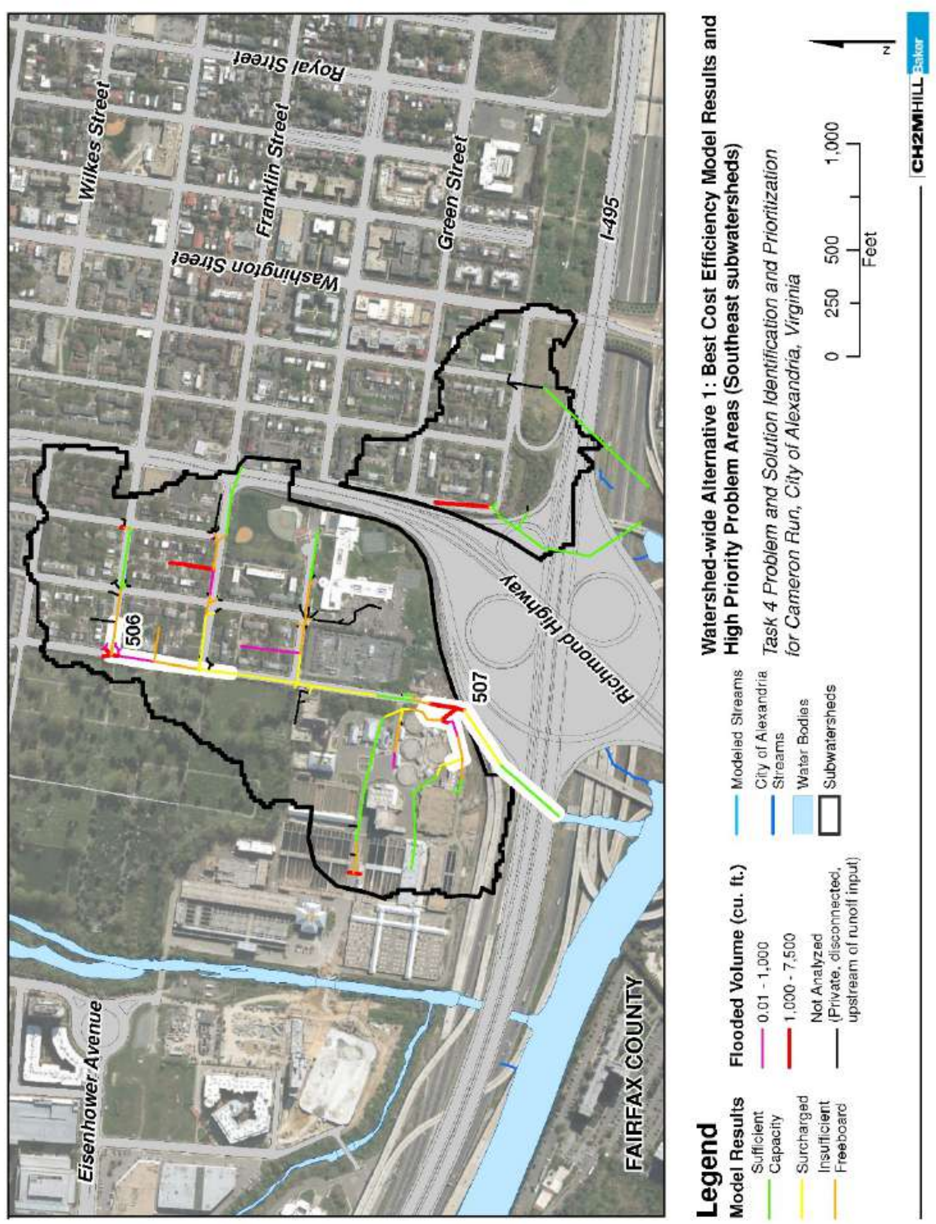


FIGURE 5-4B
Alternative 2: Benefit/Cost Model Results (Southeast subwatershed)
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

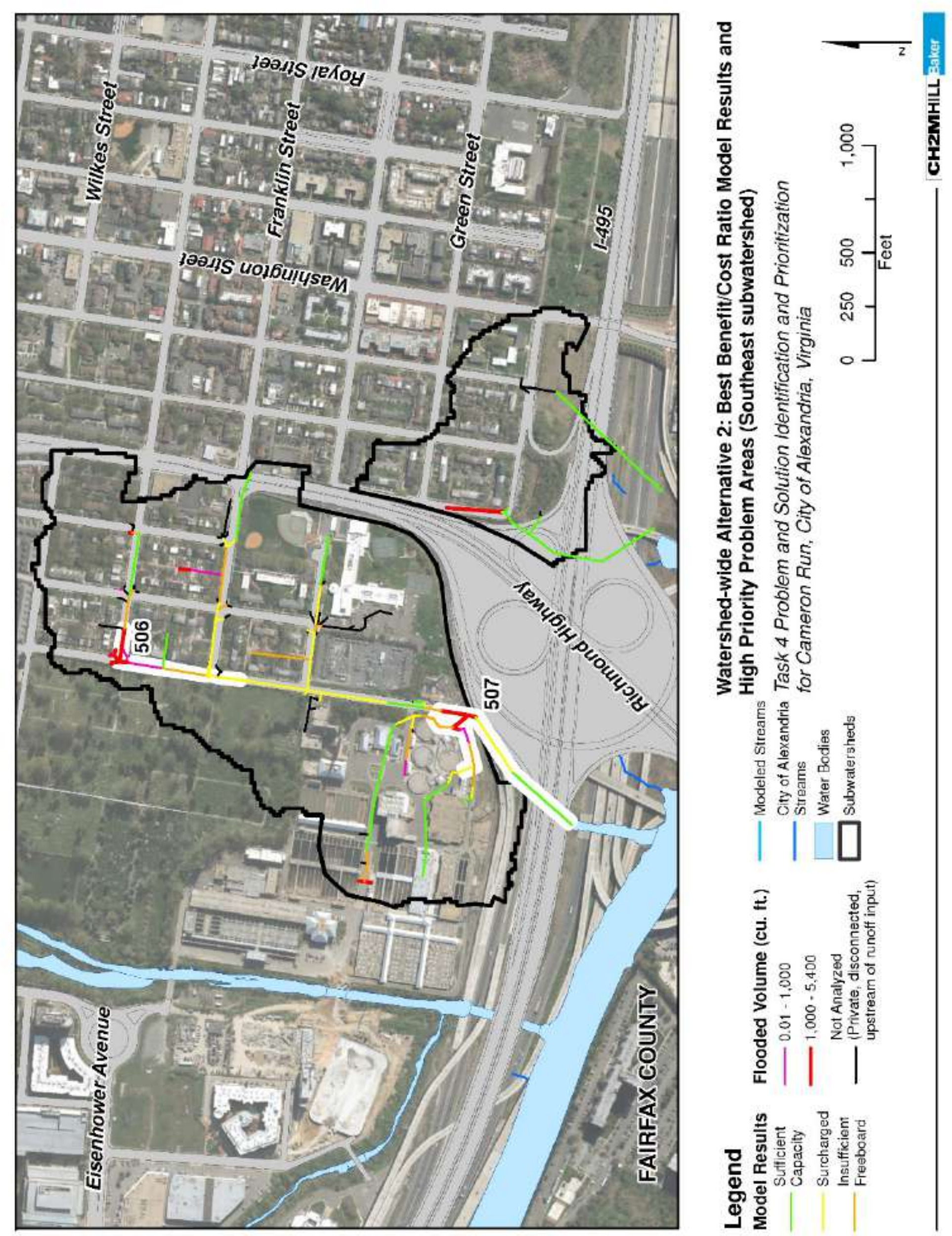
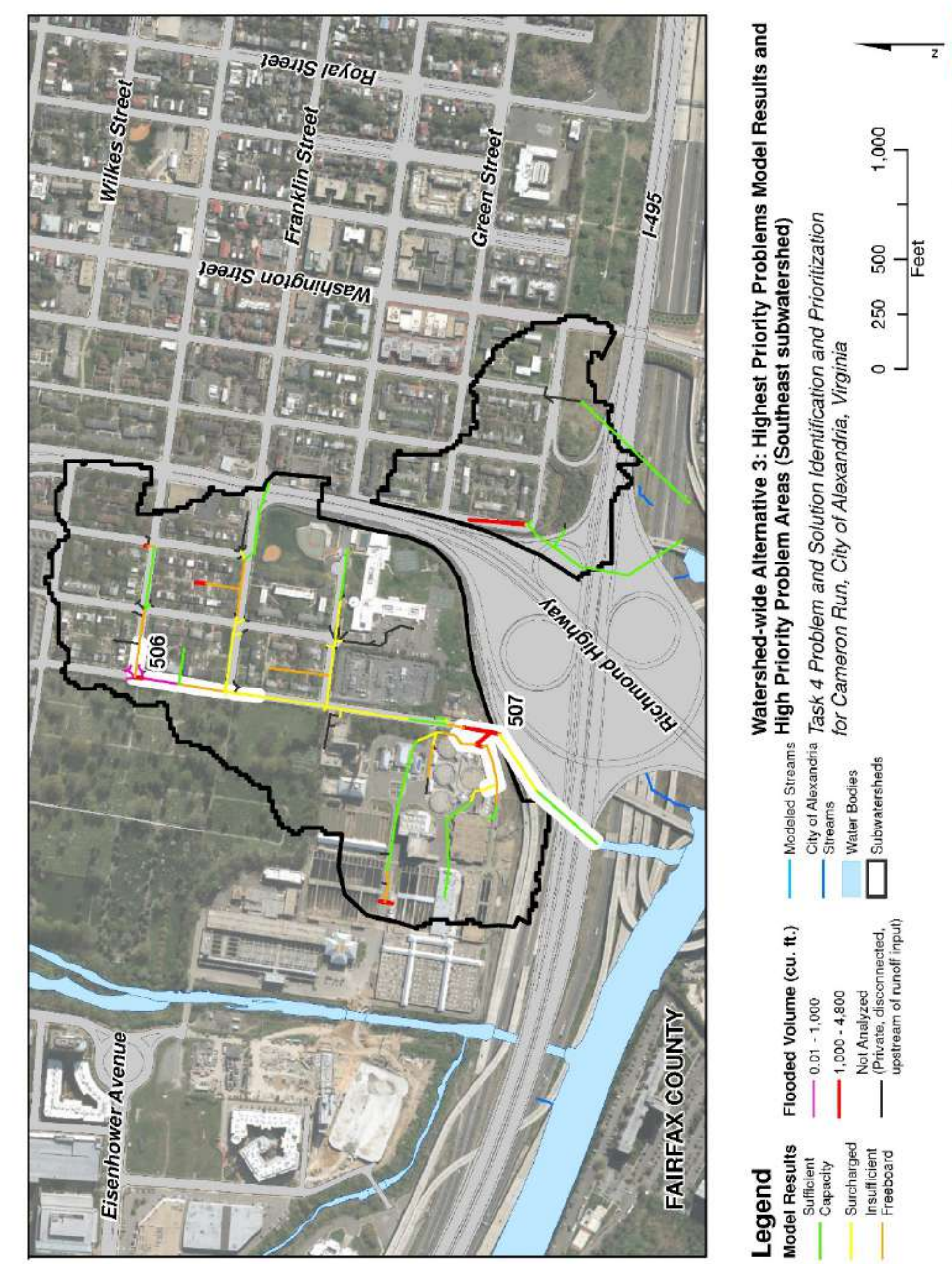


FIGURE 5-5B
Alternative 3: Highest-priority Problem Area Model Results (Southeast subwatershed)
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



5.4.5 Scoring and Prioritization Results

The results for each alternative generally reflect the objective of that particular alternative. A summary of the results is provided in Table 5-7. A model was run for each of the alternatives, so the alternative-specific results presented in Table 5-7 may differ slightly from the results generated from the technology-specific model runs used to evaluate each solution type.

Alternative 1 included the solution with the lowest cost per gallon of flood reduction for each problem area from the initial model runs, and as a result, it was also the most cost effective watershed-wide alternative. Alternative 3 was focused on providing relief in the eight highest-priority problem areas and included more than one solution for the two highest-priority problem areas. Alternative 3 provides over 17 percent more flood volume reduction than Alternative 1 and over two times the flood volume reduction as Alternative 2. However, Alternative 3 has the lowest overall benefit/cost ratio among the three watershed-wide solutions. Alternative 2 provides the greatest overall benefit/cost ratio yet its unit cost to reduce flooding is the highest at $3.01 per gallon. Alternative 1 has the second highest benefit/cost ratio with the lowest unit cost to reduce flood volume; therefore, Alternative 1 is the most cost-effective watershed-wide alternative when considering both benefits and cost efficiency together.

TABLE 5-7
Watershed-wide Alternatives Scoring and Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run

	Alternative 1 - Best Cost Efficiency	**Alternative 2 - Best Benefit/Cost Ratio**	**Alternative 3 -Highest-priority Problems**
Total Capital Cost ($ Millions)	$3.65	$3.39	$4.57
Total Benefit Score	360	394	410
Overall Benefit/Cost	99	116	90
Total Flood Reduction (MG)	2.27	1.13	2.67
Cost of Flood Reduction ($/gallon)	$1.61	$3.01	$1.71

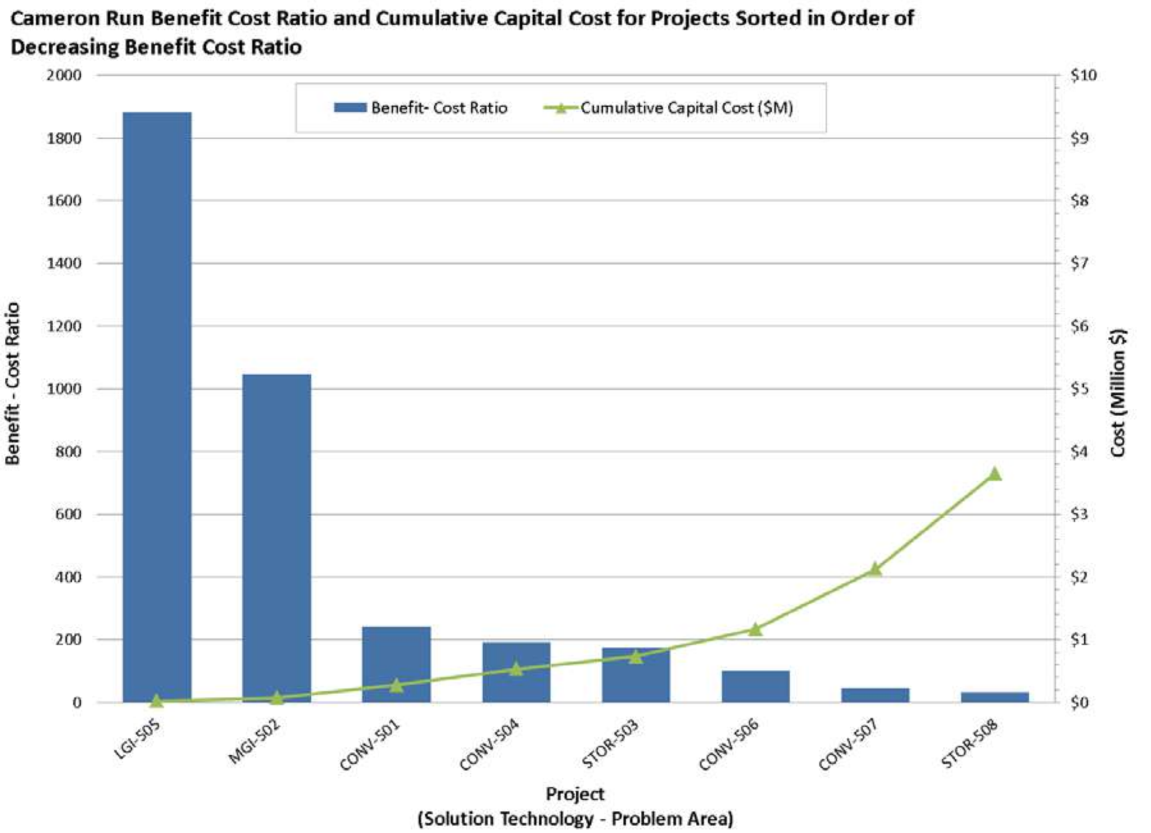
Note:
Results presented in this table are based on watershed-wide alternative models that include the selected projects documented in sections 5.4.1-5.4.3.

When developing a capital improvement plan, the benefit/cost or cost efficiency ($/gallon of flood reduction) are typically used to guide the order in which projects are implemented. Prioritization results for the three watershed-wide alternatives are presented in Figures 5-6 through 5-8. The top chart shows the benefit/cost ratio and the cumulative capital cost of the alternative. The solutions are provided in order of decreasing benefit/cost ratio; solutions with the greatest benefit/cost ratio are presented on the left and solutions with the lowest benefit/cost ratio are presented on the right. Both Figures 5-6 and 5-7 illustrate that LGI-505 has a high benefit/cost ratio, which is because Problem Area 505's drainage area has a relatively small impervious area (0.3 acre) to implement the low GI solution with a low cost to generate high benefits.

The bottom chart in Figures 5-6 through 5-8 shows the benefit/cost ratio for each solution in the watershed-wide alternative in order of increasing cost/gallon of flood reduction. The bottom charts of Figures 5-6 and 5-7 display very high cost/gallon of flood reductions for the solutions at Problem Area 503. This is because Problem Area 503 has a small volume of flooding compared with other problem areas. The cost to mitigate this relatively small flooding volume results in high cost per gallon as shown in the figures.

Both charts show the cumulative capital cost plotted on the secondary axis. The solutions on both charts are named by the technology: conveyance (CONV), storage (STOR), low GI (LGI), medium GI (MGI), or high GI (HGI), and the problem area number.

FIGURE 5-6
Alternative 1: Best Cost Efficiency Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



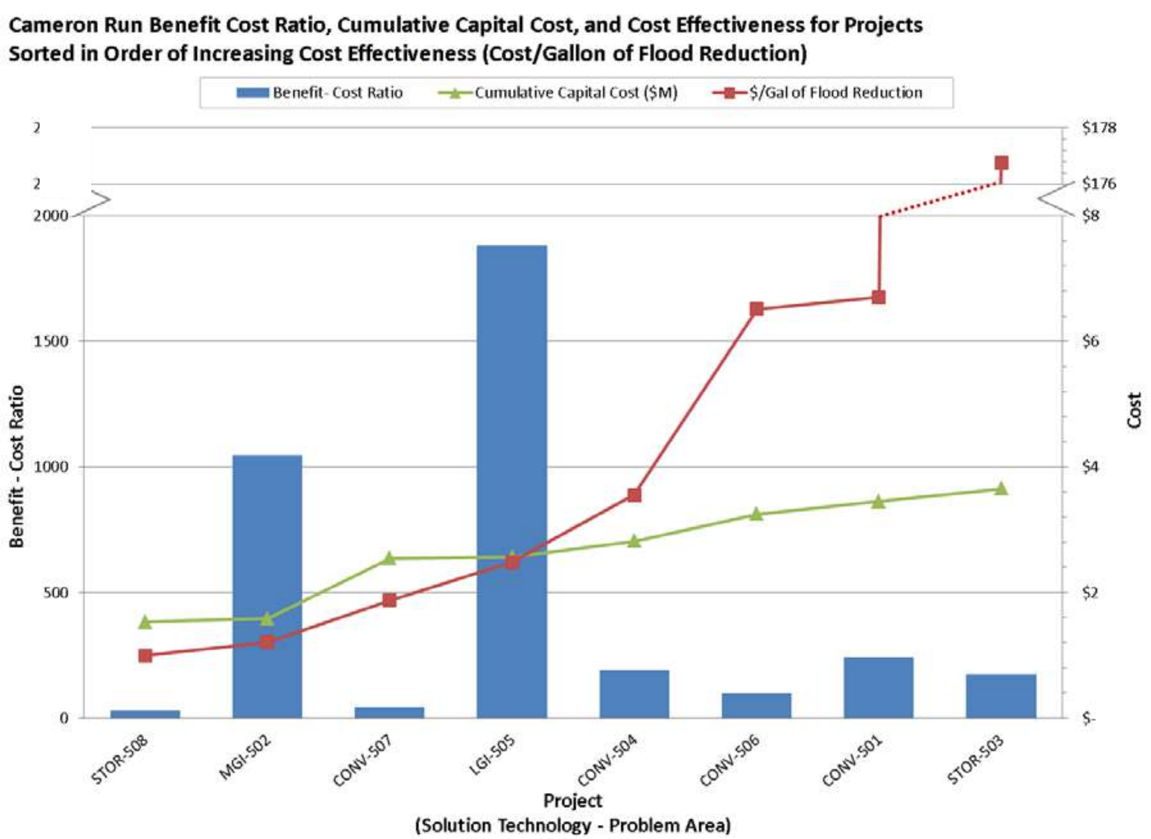
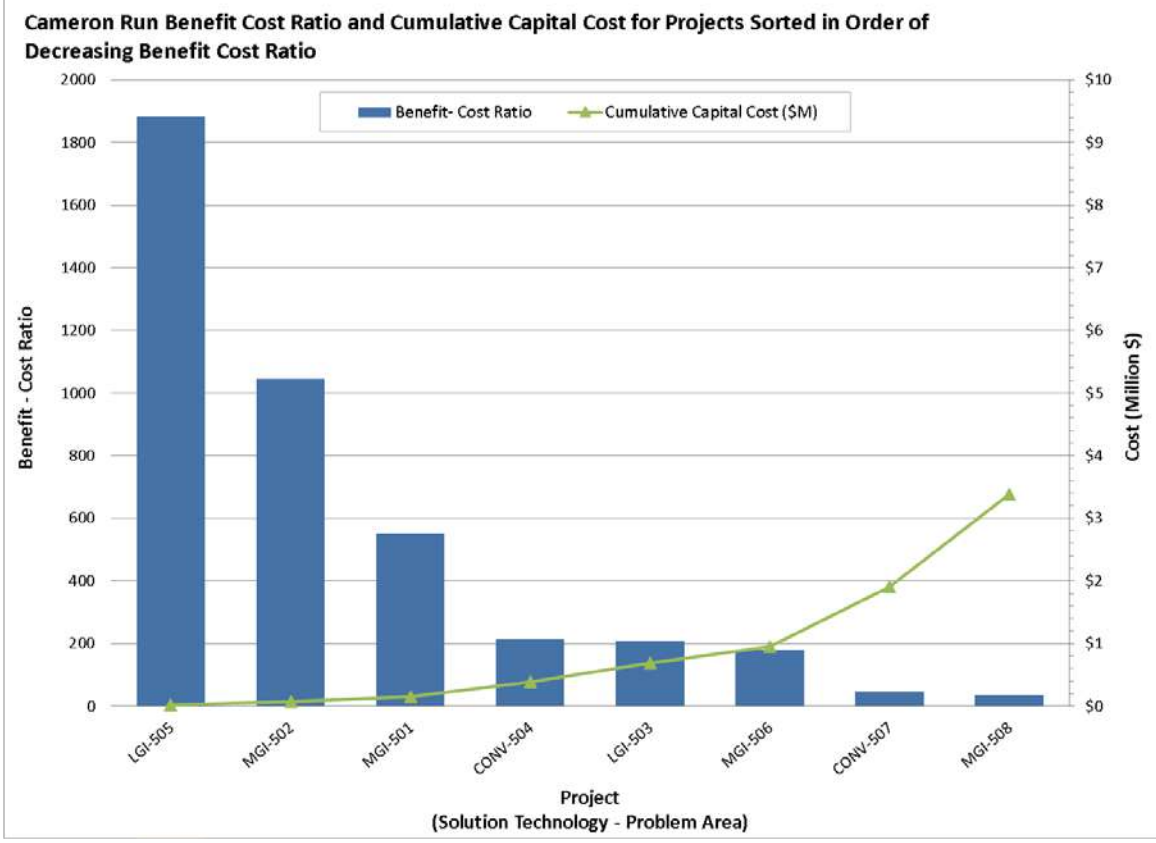


FIGURE 5-7
Alternative 2: Best Benefit/Cost Ratio Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run



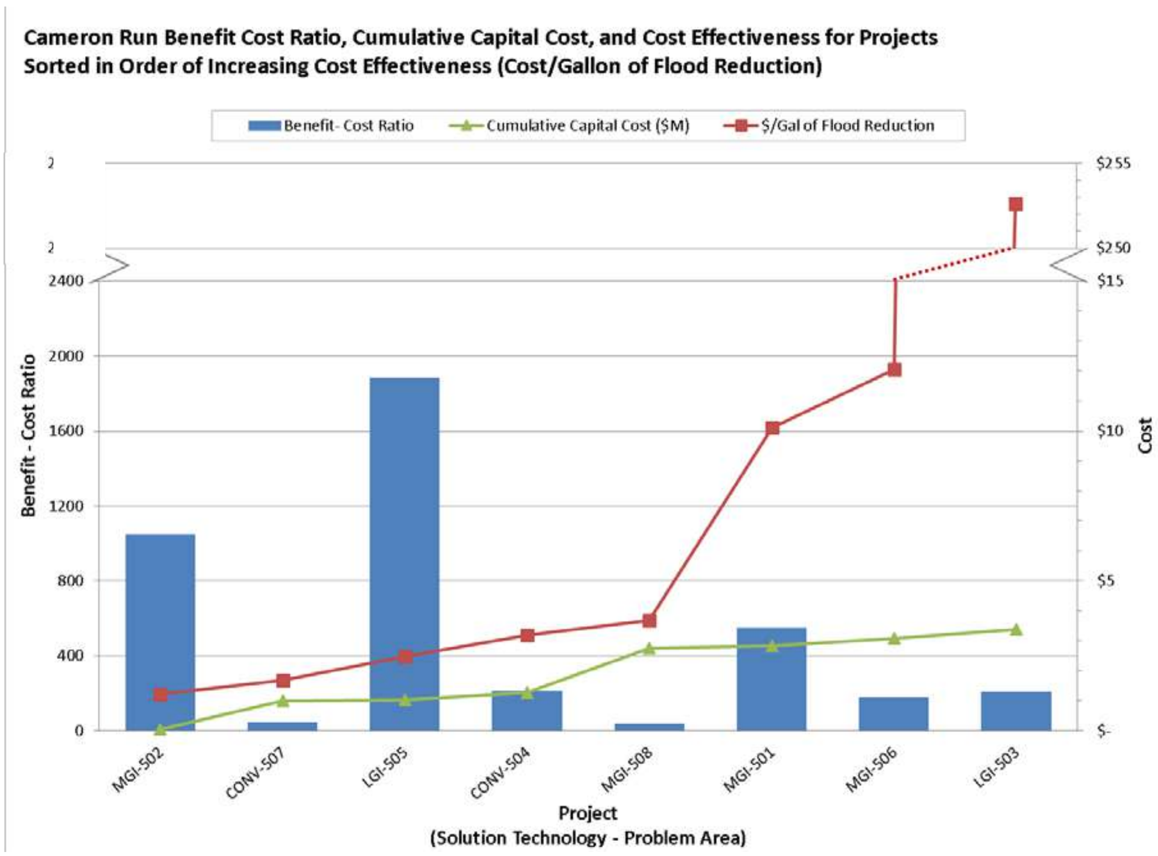
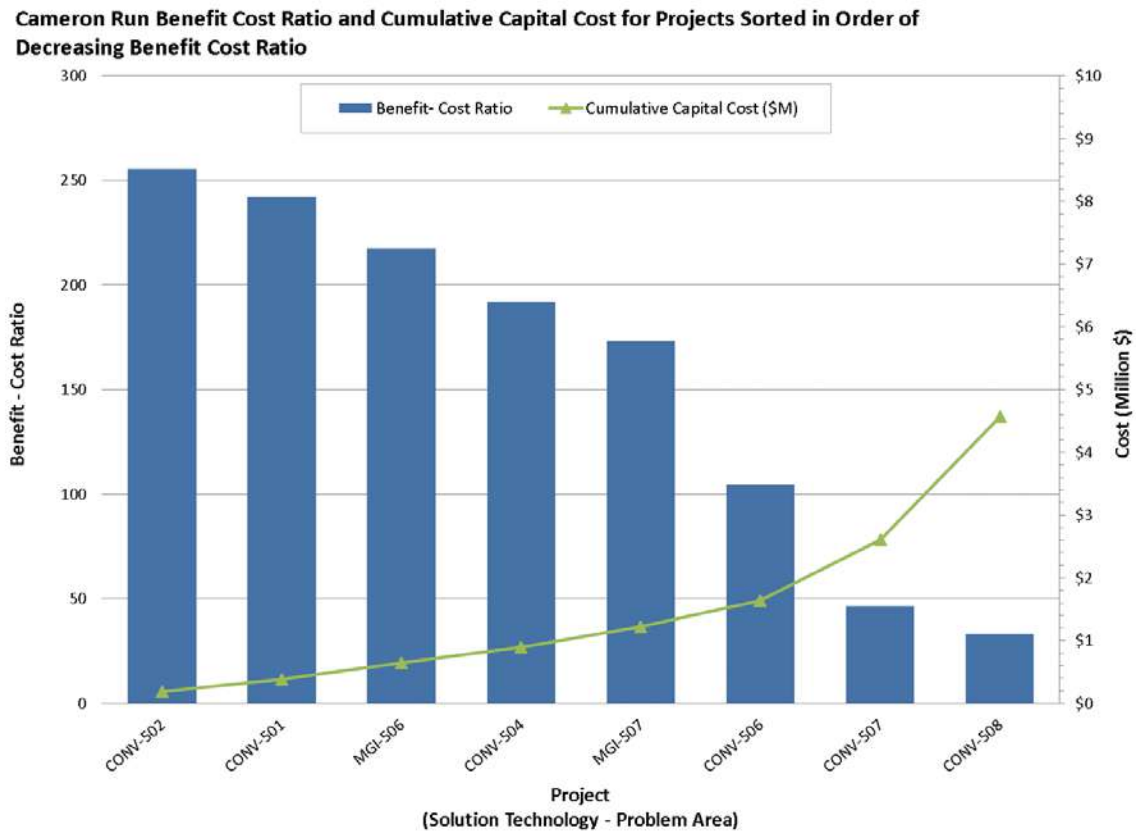
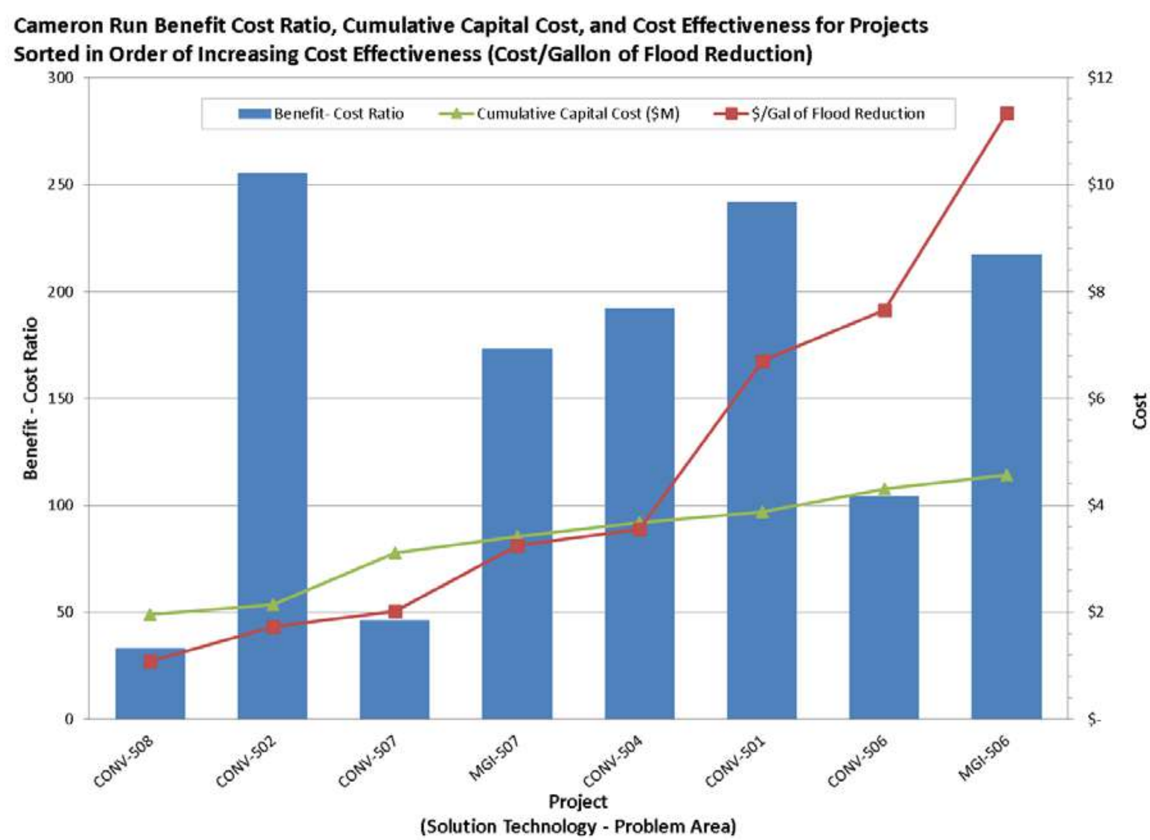


FIGURE 5-8
Alternative 3: Highest-priority Problems Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run





SECTION 6

Summary

The objectives of Task 4 were to 1) identify and prioritize capacity problems based on modeling results from Task 2 of this project, and 2) develop and prioritize solutions to address those problems. The first objective was accomplished in two steps. The first step included evaluating each stormwater junction in the drainage network using a scoring system to identify problems based on several criteria, including the severity of flooding, proximity to critical infrastructure and roadways, identification of problems by City staff and the public, and opportunity for overland relief. In the next step, high-scoring junctions (that is, higher-priority problems) were grouped together to form high-priority problem areas. In total, eight high-priority problem areas were identified in the Cameron Run watershed.

The second objective involved developing and prioritizing solutions to address capacity limitations within the eight high-priority problem areas. To accomplish this objective, strategies involving different technologies were examined, including improving conveyance by increasing hydraulic capacity, reducing capacity limitations by adding distributed storage to the system, and reducing stormwater inflows by implementing GI. Each of these strategies required a different modeling approach. Conveyance improvements were modeled by increasing pipe diameters in key locations within the problem areas, storage was added as storage nodes based on a preliminary siting exercise, and GI was modeled as a reduction in impervious area at three different implementation levels: high, medium, and low. A single model run was set up and run for each strategy addressing all eight high-priority problem areas and the results were compiled for the alternative and prioritization evaluation. Solutions were evaluated based on several criteria, including drainage improvement and flood reduction, environmental compliance, sustainability and social benefits, asset management and maintenance implications, constructability, and public acceptance. Planning-level capital costs were developed for each solution to facilitate a benefit/cost analysis and prioritization process.

The results of the solution identification and prioritization analysis show the following results for Cameron Run:

- Solution technology performance:
  - GI generally has the greatest overall benefit as defined by the solution evaluation scoring system described in this report.
  - Conveyance solutions and storage solutions generally provide the greatest flood reduction of the technologies and approaches analyzed in Cameron Run.
  - Combination of conveyance or storage projects combined with GI generally provides the greatest benefit and flood reduction.
- Costs:
  - Low to medium levels of GI implementation generally has the greatest cost/benefit score but do not usually meet minimum threshold for flood reduction.
  - Conveyance and storage projects generally provide the most economical stormwater volume reduction in terms of dollars per gallon of flood reduction within a high-priority problem area.
  - Combination of conveyance and GI generally provides the greatest overall benefit/cost score.

The following three watershed-wide alternatives were developed:

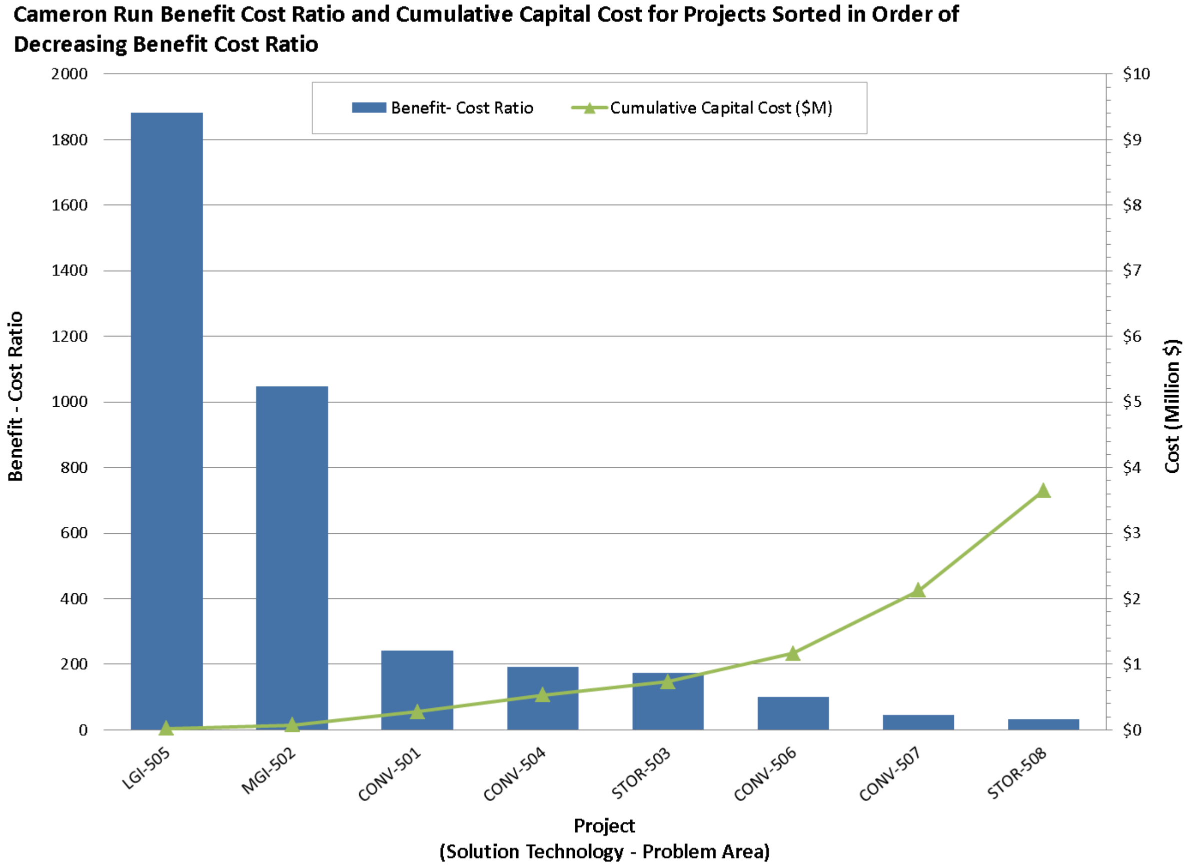
- Alternative 1: Most cost-effective solution for each problem area (lowest dollar-per-gallon of flood reduction)
- Alternative 2: Best benefit/cost ratio for each problem area (highest benefit/cost ratio)
- Alternative 3: Combination of best projects to resolve the worst problem areas

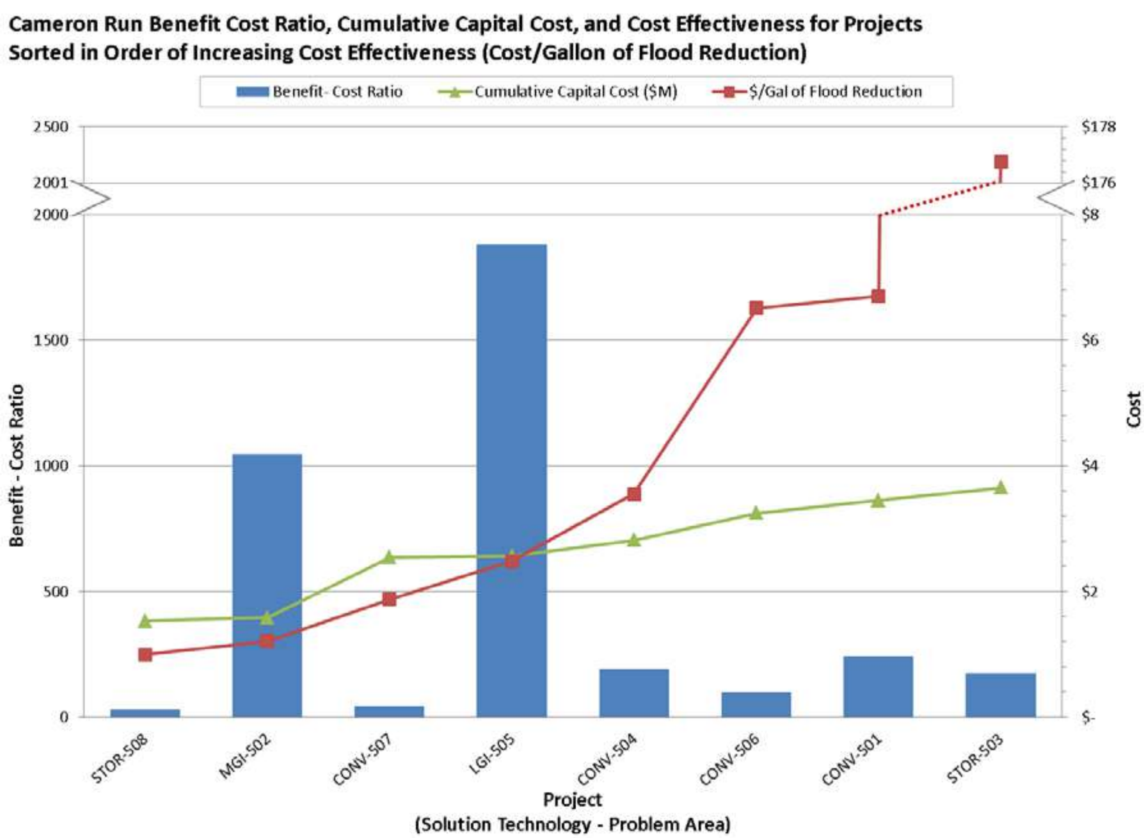
The results for each alternative generally reflects the objective of that particular alternative. A summary of the results was provided in Table 5-7. Alternative 3 was focused on providing relief in the eight highest-priority problem areas and included more than one solution for the two highest-priority problem areas. Alternative 3 provides over 17 percent more flood volume reduction than Alternative 1 and two times as much as Alternative 2; however, Alternative 3 has the lowest benefit/cost ratio. Alternative 2 provides the best overall benefit/cost score but it also has the highest cost-per-gallon of flood reduction. Therefore, Alternative 1 is the most cost-effective watershed-wide alternative with the second highest benefit scores and the lowest unit cost to reduce flood volume. The suggested prioritizations of watershed-wide Alternative 1 projects are provided in Figure 6-1; projects can be prioritized either based on overall benefit/cost ratio or cost efficiency (cost per gallon of flood reduction).

It should be noted that the model does not include analysis on private property, but applies assumed runoff loads as inputs to the public conveyance system. The City chose not to include existing private or most public stormwater management facilities (for example, detention and retention ponds) upstream of the modeled collection system because of the limited available information on these facilities and a concern that the facilities may not be performing as designed. When the City moves forward into detailed evaluation and design of selected projects, it will be important to fully evaluate and account for the benefits of any existing stormwater management facilities.

The hydraulic modeling results and costs presented in this report should be reviewed with the understanding that several assumptions were made to fill data gaps in the hydraulic model, and proposed solutions and costs were developed on a planning level.

FIGURE 6-1
Alternative 1: Best Cost Efficiency Prioritization Results
City of Alexandria Storm Sewer Capacity Analysis – Cameron Run





SECTION 7

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Appendix A
Conveyance Solutions

Appendix A - Conveyance Solutions

Summary of Conveyance Solutions Developed for Cameron Run High-Priority Problem Areas

Problem Area	FacilityID	Upstream Node Name	Downstream Node Name	Length ft	Proposed Shape	Existing Diameter/ Height (ft) x Width (ft)	Proposed Diameter/ Height (ft) x Width (ft)	Conduit Slope	Number of Barrels	Roughness
501	003462STMP	000704SMH	000705SMH	209	Circular	1.75	2.5	0.61	1	0.013
501	003466STMP	000705SMH	000706SMH	142	Circular	1.75	2.5	0.54	1	0.013
501	003469STMP	000706SMH	000707SMH	150	Circular	2.25	3.5	0.12	1	0.013
502	002605STMP	000694SMH	000693SMH	170	Circular	1.5	2	0.52	1	0.013
502	002607STMP	000695SMH	000694SMH	148	Circular	1.5	2	0.46	1	0.013
502	002609STMP	000696SMH	000695SMH	54	Circular	1.25	2	0.45	1	0.013
502	003440STMP	000697SMH	000696SMH	36	Circular	1.25	1.25	3.07	1	0.013
502	003442STMP	000698SMH	000697SMH	117	Circular	1.25	2.5	0.22	1	0.013
502	003443STMP	000699SMH	000698SMH	184	Circular	1.25	1.5	7.65	1	0.013
503	003407STMP	000675SMH	000676SMH	54	Circular	1.5	2	2.28	1	0.013
503	003408STMP	000639SMH	000675SMH	142	Circular	1.25	1.5	2.38	1	0.013
503	003409STMP	000676SMH	000677SMH	180	Circular	5.5	6.5	1.61	1	0.013
503	003411STMP	000677SMH	000678SMH	223	Circular	5.5	7	1.17	1	0.013
504	005634STMP	003547IN	003546IN	71	Circular	3	3.5	1.64	1	0.013
504	005635STMP	003546IN	003537IN	352	Circular	3	3.5	1.65	1	0.013
504	005637STMP	003549IN	003547IN	26	Circular	2.5	2.5	3.49	1	0.013
505	002419STMP	001300IN	001301IN	209	Circular	1.5	1.5	2.41	1	0.013
505	002421STMP	001301IN	000500SMH	12	Circular	1.75	1.75	6.00	1	0.013
505	003979STMP	000500SMH	000851SMH	179	Circular	2	2.5	1.74	1	0.013
505	004212STMP	000850SMH	000852SMH	234	Circular	1.5	2	7.16	1	0.013
505	004213STMP	000851SMH	000850SMH	31	Circular	2	2	3.92	1	0.013
506	000236STMP	000061SMH	000062SMH	156	Circular	2	3.5	0.14	1	0.013
506	000251STMA	000048ND	000064SMH	7	Circular	2.5	3.5	0.36	1	0.013
506	000251STMB	000063SMH	000048ND	209	Circular	2.5	3.5	0.36	1	0.013
506	000253STMA	000052ND	000063SMH	169	Circular	2.5	4	0.10	1	0.013
506	000253STMB	000062SMH	000052ND	34	Circular	2.5	4	0.10	1	0.013
506	000255STMP	000064SMH	000049ND	45	Circular	2.5	4.5	0.13	1	0.013
506	015107STMP	000049ND	000065SMH	117	Circular	3	4.5	0.13	1	0.013
507	000277STMP	000076SMH	009284IN	128	Circular	3.5	3.5	1.30	1	0.013
507	007038STMP	004516IN	004526IN	31	Circular	3	3	3.05	1	0.013
507	007051STMP	001738SMH	001739SMH	44	Circular	2	3	0.30	1	0.013
507	007052STMP	001739SMH	004526IN	66	Circular	2	3	0.36	1	0.013
507	007053STMP	004526IN	009284IN	90	Circular	3	3	2.02	1	0.013
507	007317STMP	004513IN	004514IN	104	Circular	2	2	1.19	1	0.013
507	007318STMP	001707SMH	004513IN	69	Circular	1.25	2	0.44	1	0.013
507	007320STMP	004514IN	004515IN	77	Circular	2	2	1.32	1	0.013
507	007321STMP	004515IN	004516IN	23	Circular	2.5	2.5	3.05	1	0.013

Appendix A - Conveyance Solutions

Summary of Conveyance Solutions Developed for Cameron Run High-Priority Problem Areas

Problem Area	FacilityID	Upstream Node Name	Downstream Node Name	Length ft	Proposed Shape	Existing Diameter/ Height (ft) x Width (ft)	Proposed Diameter/ Height (ft) x Width (ft)	Conduit Slope	Number of Barrels	Roughness
507	015105STMP	009284IN	000077SMH	36	Circular	3.5	3.5	-0.15	1	0.013
507	015123STMP	000077SMH	002399ND	312	Circular	4	4	-0.38	1	0.013
507	CRpipe17	002399ND	Node5183	364	Rectangular	3.5	4 x 7	0.14	1	0.013
508	004208STMP	002485IN	002486IN	218	Circular	3.5	8.5	0.43	2	0.011
508	004903STMP	002486IN	003546SMH	309	Circular	3.5	8.5	0.38	2	0.013
508	013331STMP	003546SMH	003547SMH	49	Circular	3.5	8.5	0.98	2	0.013

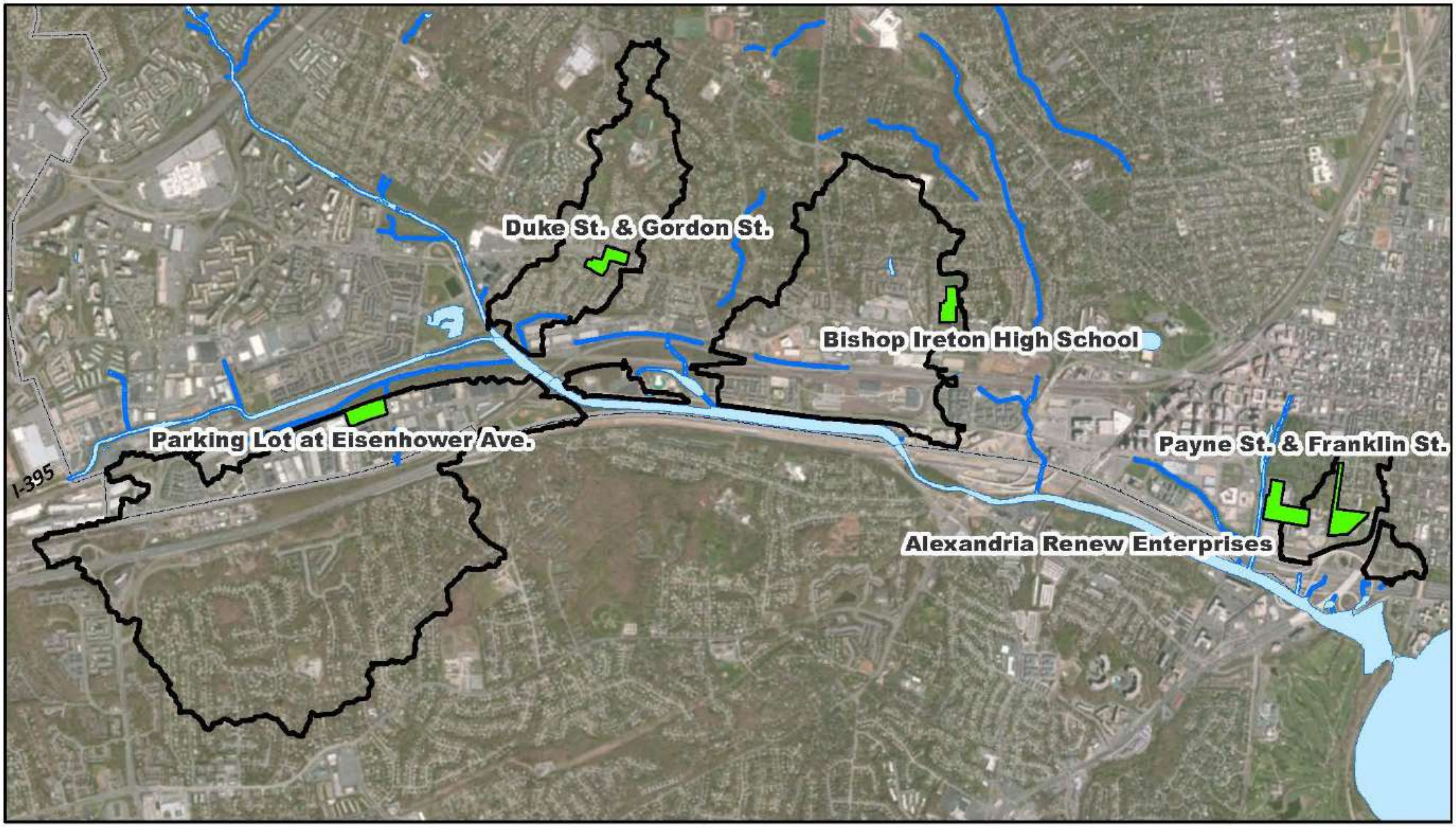
Appendix B
Storage Solutions

Appendix B - Storage Solutions

Summary of Storage Solutions Developed for Cameron Run High Priority Problem Areas

Problem Area	Storage ID	Overflow Node	Discharge Node	Storage Area (ac)	Storage Area (ft^2)	Overflow Weir Crest	Overflow Weir Crown	Storage Invert Elevation (ft)	Storage Rim Elevation (ft)	Storage Depth (ft)	Storage Volume (ft^3)	Notes
503	1	000677SMH	000678SMH	0.17	7,441	54.61	57.01	47.00	54.61	7.61	56,624	Water max depth is 1.65 ft
504	2	003546IN	003537IN	0.11	4,911	76.02	79.72	70.00	76.02	6.02	29,565	Water max depth is 4.08 ft
507	3	004526IN	002399ND	0.29	12,655	7.08	10.47	3.50	7.08	3.58	45,341	
508	4	002485IN	003546SMH	0.56	24,436	34.20	40.16	30.00	34.2	4.20	102,629	

Appendix C
Green Infrastructure Concept Plans



Legend

- Concept Locations
- City of Alexandria Streams
- Water Bodies
- Subwatersheds

Cameron Run Watershed Green Infrastructure
Concept Plans Locations

Task 4 Problem Identification and Prioritization for Cameron Run
City of Alexandria, Virginia

0 3,000 6,000
Feet

N

CH2MHILL Baker

Potential Sites for Task 4 Green Infrastructure Concepts Development in Cameron Run Watershed

PREPARED FOR: City of Alexandria TE&S

COPY TO: File

PREPARED BY: Michael Baker International

DATE: March 11, 2015

The following is documentation of the sites identified for green infrastructure (GI) concept development in the Cameron Run watershed. In addition to field notes that describe the sites and the proposed GI, the pros and cons of GI implementation are also listed. The inspections were conducted in March 2015. The conceptual plan corresponding to each site can be found as an attachment to this documentation.

Duke St. & Gordon St.

Parking Lot along Duke St. (facing southeast)

Grass area south of Duke Street (facing east)

Program Type: Green Parking and Green Roofs

GI Concepts: Bioretention/Planters, Green/Blue Roofs, Porous Pavement

Field Notes:

- Location is at the intersections of Duke Street and North/South Gordon Street, divided by Duke Street into two sites north and south of the road.
- The site is at a bottleneck within the stormsewer system of Cameron North subwatershed which merges three upstream pipe branches into one downstream pipeline.
- The building north of Duke Street planned for green roofs is shared by a restaurant (currently closed) and a medical office. The building south of Duke Street is used for private commercial purposes.
- Both sites have underutilized parking areas.
- These are small grass areas on both sides of Duke Street that could be converted into bioretention/planters. The site south of Duke Street has the most potential with larger open space along the north and east sides of the parking lot.

- Proposed GI Concept
    - Install two to three bioretention areas on either sides of Duke Street.
    - Install green roofs on a portion of the two commercial buildings.
    - Install porous pavement in the parking lots on both sides of Duke Street.

Pros:

- The installation of GI facilities at this bottleneck location can reduce the discharge of the downstream pipes.
- The open grass areas along Duke Street provide sufficient areas to implement bioretention/planters facilities.
- The parking lots with low occupancy are spacious to implement porous pavement.
- Stormwater manholes/inlets can be found in close proximity to the planned GI locations which will make diverting runoff into the GI facilities feasible as well as providing tie-in to the existing storm sewer system.

Cons:

- The heavy traffic flow through Duke Street may be influenced during the construction work at the location.
- The buildings are privately-owned with utilities on the roofs, which may affect the feasibility to implement green roofs.
- During construction of the porous pavement, business at the commercial property may be negatively affected.
- Environmental impacts towards the community south of the location may be possible during the construction process of bioretention/planters facilities.

Parking Lot at Eisenhower Ave.

Parking Lot along Eisenhower Ave. (facing southwest)

Tree Sites at the Parking Lot (facing northeast)

Program Type: Green Parking

GI Concepts: Bioretention/Planters, Porous Pavement

Field Notes:

- Location is a parking lot east of 5001 Eisenhower Avenue which appears to be vacant.
- The parking lot is used to service the office building but currently is unutilized.
- The majority of the storm sewer inlets are clogged with debris and should be removed.
- A bioretention site is recommended along the northern edge of the parking lot near the storm pipe outlet.
- Planter areas within the parking lot where trees have either died or have been removed can be converted into small rain gardens. The parking spaces can be converted to porous pavement (or pavers) to increase infiltration of runoff.
- Proposed GI Concept
    - Install a bioretention area near the outlet in the parking lot.
    - Install rain gardens within the planters without trees.
    - Install porous pavement in the parking spaces of the site.

Pros:

- Due to the size of the parking lot, there appears to be a lot of opportunity to implement GI practices.
- Planters without trees are ideal sites to construct rain gardens with enhanced media and plants.
- A combination of different GI practices at this site can enhance the benefit efficiency.

Cons:

- Installation of porous pavement may affect the access to the parking lot for a period of time.
- Cautious construction work to install porous pavement is necessary due to several electric lamp posts in the parking lot.
- Precautions will have to be taken to ensure the porous pavement does not become clogged.
- Increased utilization of the parking lot could affect implementing the bioretention cell along the north edge of the parking lot.

Payne St. & Franklin St.

West Side of Payne Street (facing south)

Unnamed Alley (facing south)

Program Type: Green Streets/Alleys

GI Concepts: Bioretention/Planters, Surface Storage (Blue Streets)

Field Notes:

- Location is from the intersection of Gibbon Street and Fayette Street to the intersection of Payne Street and Jefferson Street.
- The narrow street is particularly crowded on the west side. After speaking with a resident, we were informed that these cars are from commuters who park on the street and walk through the cemetery to Eisenhower Ave Metro Station.
- Private houses with electrical lines are on the east side of the street.
- A lot of utilities can be observed on the street.
- Proposed GI Concept:
    - Install several “bump out” bioretention cells along the west side of Payne Street.
    - Convert the alley between Jefferson Street and Franklin Street to a blue street.

Pros:

- The bioretention cells can retain and treat excessive storm runoff along Payne Street.
- Payne Street is sufficiently wide to incorporate bioretention "bump outs" at curb extension areas.
- The unnamed alley between Jefferson Street and Franklin Street has little traffic to be affected by the construction activities.

Cons:

- The construction of GI facilities near private houses should use cautions to minimize negative environmental impacts to the community.
- The bioretention cells on the west side of Payne Street will decrease the parking capacity for commuters’ cars.
- The narrow area of the unnamed alley may not provide sufficient capacity to retain excessive runoff from adjacent road and roof tops.

Alexandria Renew Enterprises

Building G: Proposed Green Roof (facing northeast)

Raised inlet (facing east)

Program Type: Green Buildings and Green Roofs

GI Concepts: Bioretention/Planters, Green/Blue Roofs, Porous Pavement

Field Notes:

- Location is the City Sanitation Authority for wastewater treatment near the corner of the Capital Beltway and Richmond Highway.
- Alexandria Renew Enterprises (ARE) has been discussing converting the roof of Building G to a green roof but there are no plans yet.
- The area east of Building J appears to be a non-functioning bioretention area. Currently, water bypasses the majority of the area because it is not graded properly and the grated structure is raised too high. This is a good opportunity for a retrofit.
- Several locations at ARE have obvious flooding problems with ponding surface water.
- Proposed GI Concept:
    - Improve the bioretention area east of Building J so that it functions properly and treats roof runoff from surrounding buildings.
    - Install a green roof on top of Building G
    - Install two bioretention cells in the grass areas near Building 22 to treat road and roof runoff.
    - Install porous pavement in the parking spaces of the site.

Pros:

- The existing non-functional bioretention east of Building J can be reconstructed with less investment and efforts than installing a new bioretention site due to the existing raised inlets.
- The ARE management team has been discussing the installation of a green roof and is supportive for more GI construction.
- The implementation of GI facilities could potentially alleviate the existing flooding problems in the plant.

Cons:

- The facilities at the City Sanitation Authority may need to follow more stringent regulations to minimize any environmental impacts to the water treatment operations.

- The large area of ARE demands multiple GI facilities with high capacities to retain and treat runoff.
- Precautions will have to be taken to ensure the porous pavement does not become clogged.

Bishop Ireton High School

High School Entrance (facing north)

Highly Occupied Parking Lot (facing west)

Program Type: Green Schools

GI Concepts: Bioretention/Planters, Cistern, Green/Blue Roofs, Porous Pavement

Field Notes:

- The private Catholic high school is located on the corner of Duke Street and Cambridge Road.
- The school building has downspouts directly connected to the storm sewer to discharge roof runoff.
- The parking lot is extensively occupied by vehicles.
- An area which was identified as a potential location for GI practices may be converted to a parking lot due to the need for additional parking spaces.
- Proposed GI Concept
  - Convert a portion of the existing roof to a green roof.
  - Convert the school's main entrance area and the football field into a bioretention area. Divert road and roof runoff to the proposed site.
  - Install porous pavement in the parking spaces of the site.

Pros:

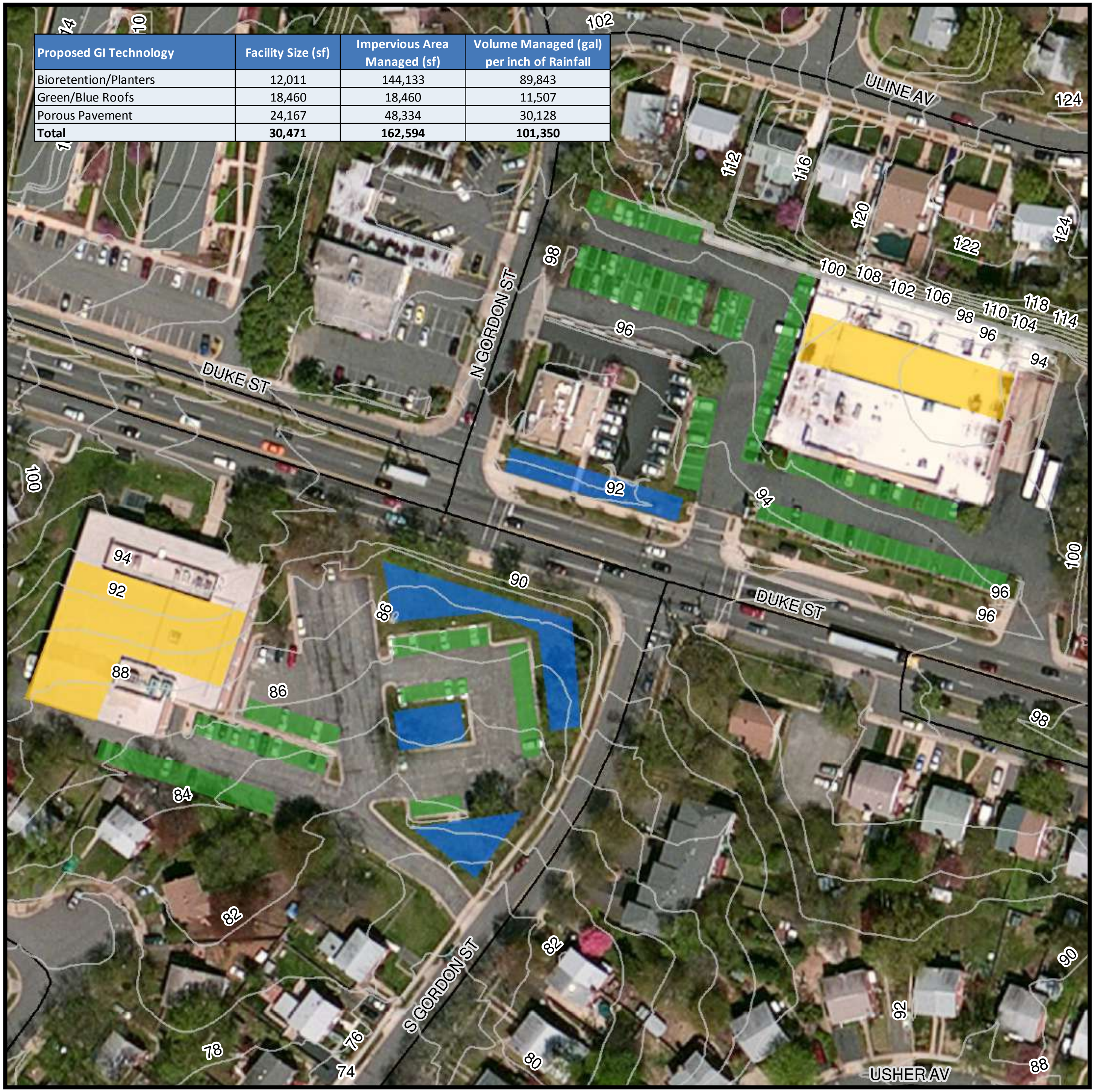
- The conveyance and treatment of roof/road runoff can decrease the flooding possibilities of the DASH facility downstream of the high school.
- The implementation of GI facilities at the high school can be demonstrative examples to play an educational role.
- The maintenance supervisor stated that the school is already looking at GI solutions throughout the property.

Cons:

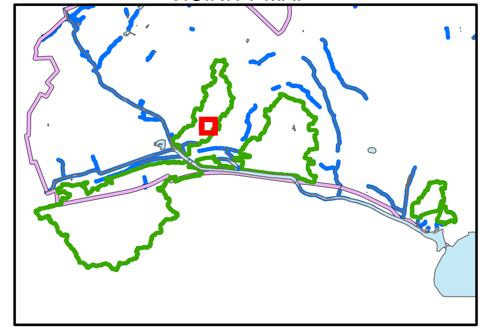
- Precautions will have to be taken during construction to ensure there is ample room for school parking.
- Precautions will have to be taken to ensure the porous pavement does not become clogged.

- Construction work must be performed with caution to maintain safe conditions for staff and students.
- The main entrance area may be converted to a parking lot.

Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal) per inch of Rainfall
Bioretention/Planters	12,011	144,133	89,843
Green/Blue Roofs	18,460	18,460	11,507
Porous Pavement	24,167	48,334	30,128
Total	**30,471**	**162,594**	**101,350**



VICINITY MAP

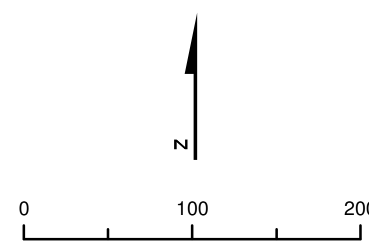


LEGEND

Contours (ft)

Green Infrastructure Concepts

- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)
- City of Alexandria Streams
- Water Bodies
- Alexandria Boundary



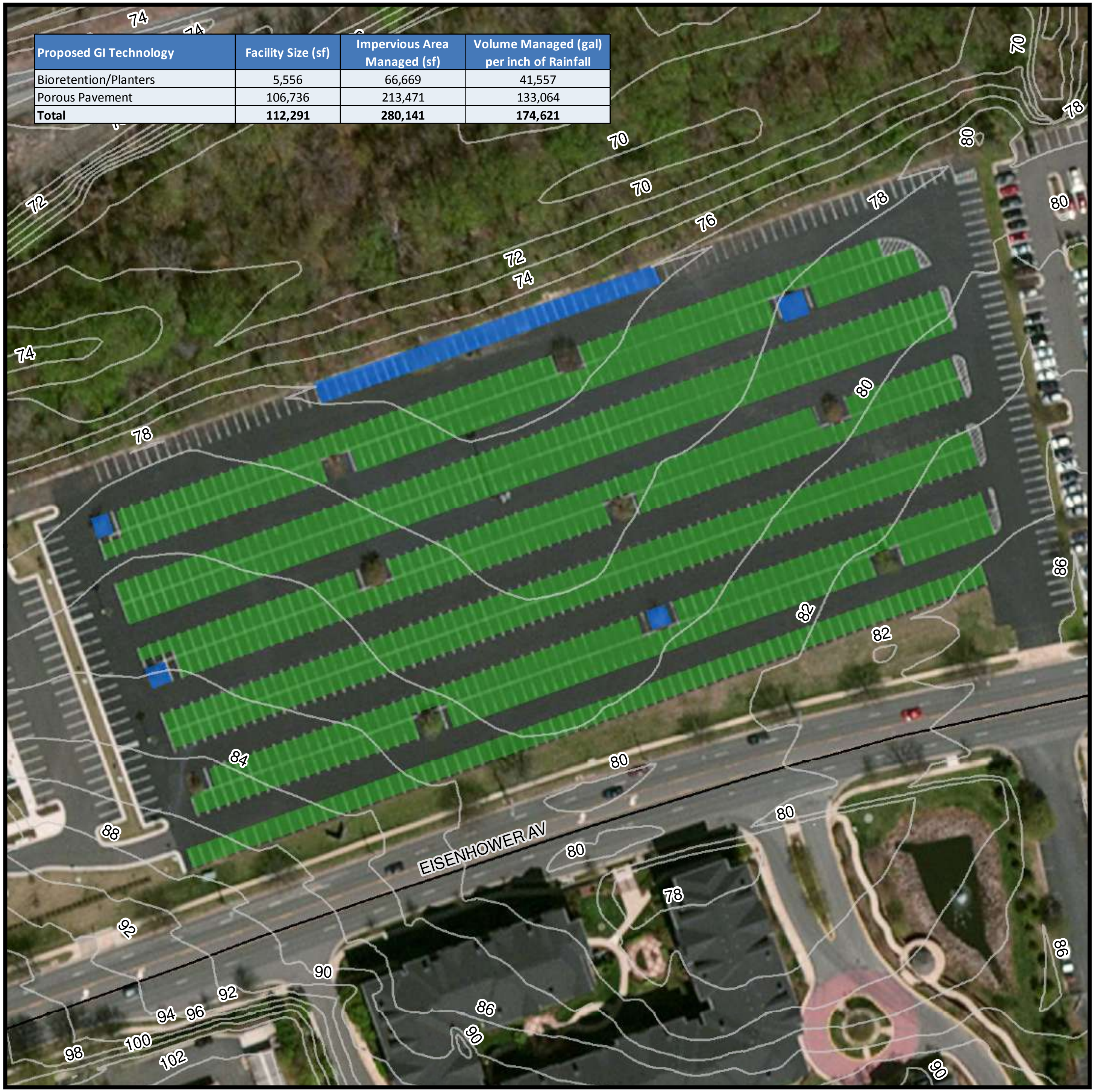
Duke St. & Gordon St.

Green Parking and Green Roofs
- Bioretention/Planters, Green/Blue Roof, Porous Pavement

Task 4 - Identify Problems and Develop Solutions

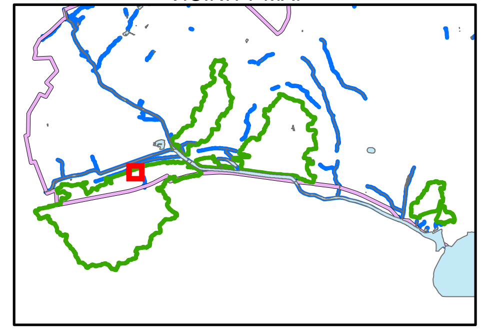
City of Alexandria Storm Sewer Capacity Analysis

CH2MHILL Baker



Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal) per inch of Rainfall
Bioretention/Planters	5,556	66,669	41,557
Porous Pavement	106,736	213,471	133,064
Total	**112,291**	**280,141**	**174,621**

VICINITY MAP

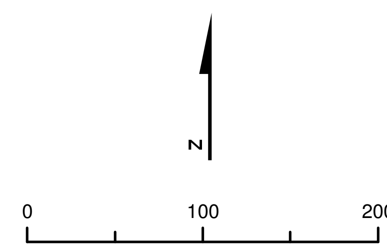


LEGEND

Contours (ft)

Green Infrastructure Concepts

- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)
- City of Alexandria Streams
- Water Bodies
- Alexandria Boundary



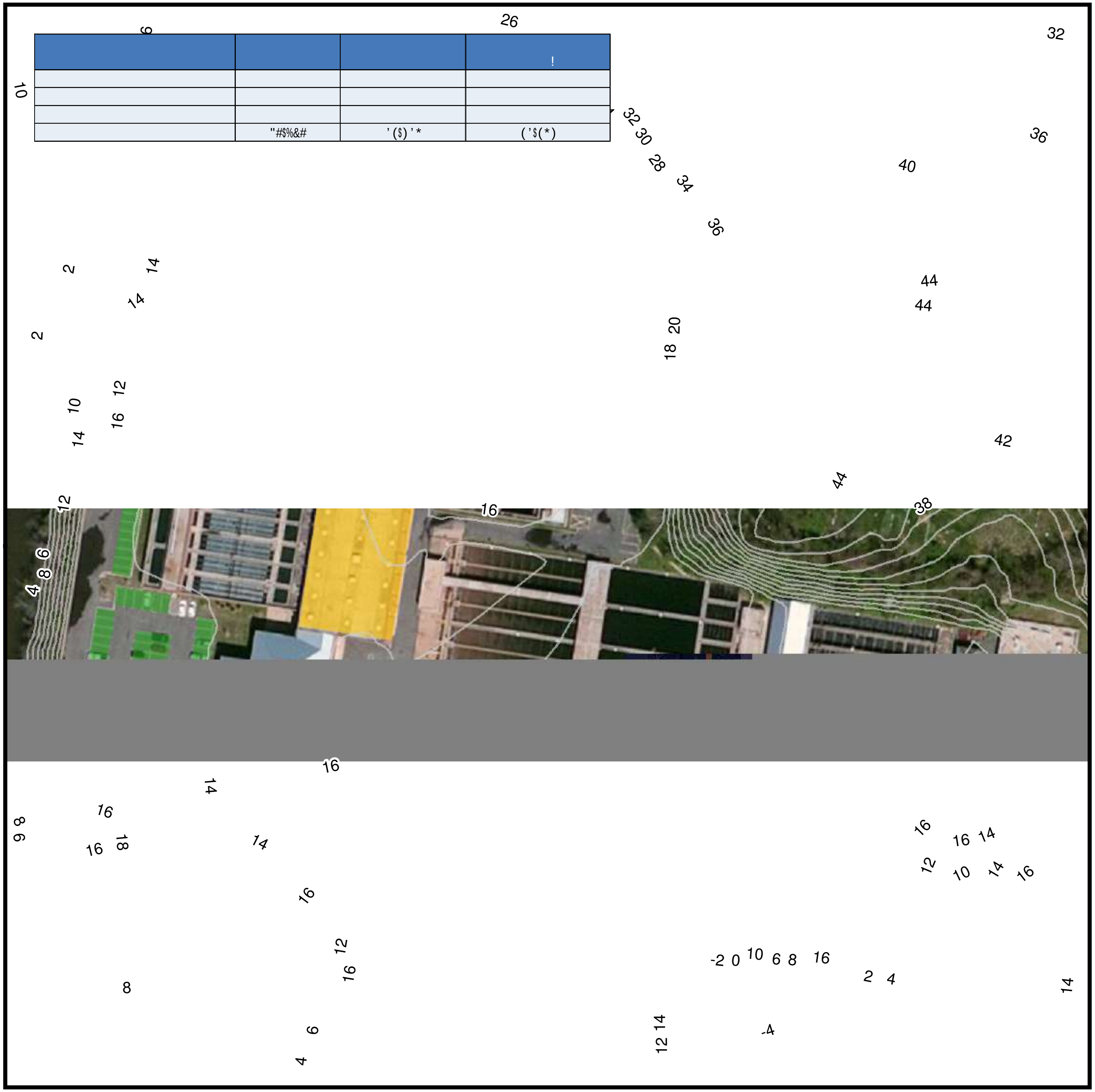
Parking Lot at Eisenhower Ave.

Green Parking
- Bioretention/Planters, Porous Pavement

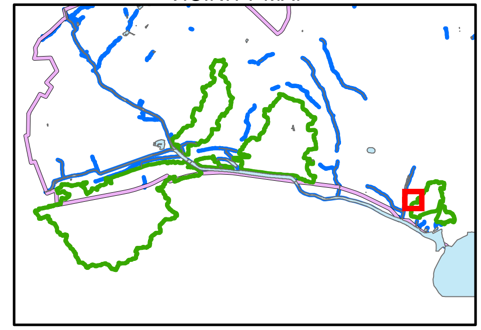
Task 4 - Identify Problems and Develop Solutions

City of Alexandria Storm Sewer Capacity Analysis

CH2MHILL Baker



VICINITY MAP



LEGEND

Contours (ft)

Green Infrastructure Concepts

Bioretention/Planters

Cisterns

Green/Blue Roofs

Porous Pavement

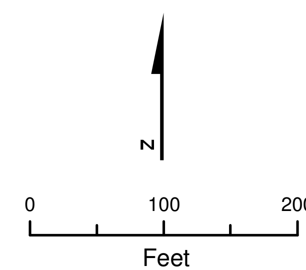
Stream Daylighting

Surface Storage (Blue Streets)

City of Alexandria Streams

Water Bodies

Alexandria Boundary



Alexandria Renew Enterprises

Green Buildings

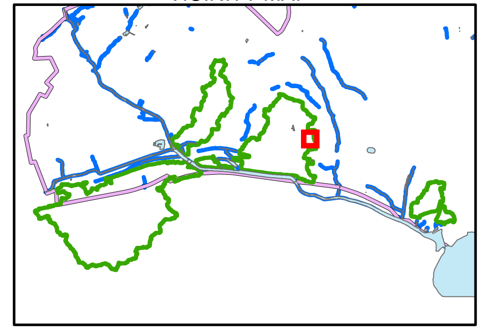
- Bioretention/Planters, Green/Blue Roofs, Porous Pavement

Task 4 - Identify Problems and Develop Solutions

City of Alexandria Storm Sewer Capacity Analysis

Proposed GI Technology	Facility Size (sf)	Impervious Area Managed (sf)	Volume Managed (gal) per inch of Rainfall
Bioretention/Planters	5,898	70,775	44,117
Cisterns	822	822	513
Green/Blue Roofs	6,549	6,549	4,082
Porous Pavement	23,990	47,981	29,908
Total	**37,259**	**126,127**	**78,619**

VICINITY MAP



LEGEND

Contours (ft)

Green Infrastructure Concepts

- Bioretention/Planters
- Cisterns
- Green/Blue Roofs
- Porous Pavement
- Stream Daylighting
- Surface Storage (Blue Streets)
- City of Alexandria Streams
- Water Bodies
- Alexandria Boundary

N

0 100 200
Feet

Bishop Ireton High School

Green School
- Bioretention/Planters, Cisterns, Green/Blue Roofs, Porous Pavement,
Task 4 - Identify Problems and Develop Solutions
City of Alexandria Storm Sewer Capacity Analysis

CH2MHILL Baker

FACT SHEET: BIORETENTION AND STORMWATER PLANTERS

Rain garden in a public park setting in Lancaster, PA

Right-of-way bioretention planting in Syracuse, NY

Bioretention areas (often called Rain Gardens) are shallow surface depressions planted with specially selected native vegetation to treat and capture runoff and are sometimes underlain by sand or a gravel storage/infiltration bed. Bioretention is a method of managing stormwater by pooling water within a planting area and then allowing the water to infiltrate into the garden soils. In addition to managing runoff volume and mitigating peak discharge rates, this process filters suspended solids and related pollutants from stormwater runoff.

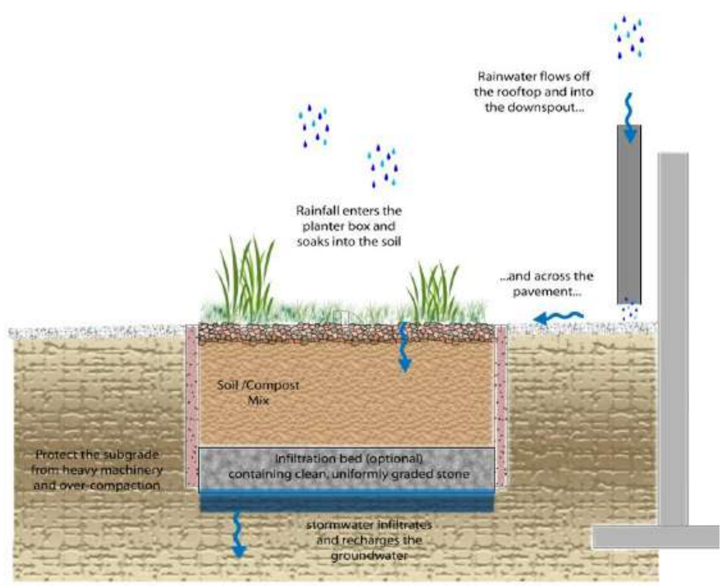
Bioretention can be designed into a landscape as a garden feature that helps to improve water quality while reducing runoff quantity. Rain Gardens can be integrated into a site with a high degree of flexibility and can balance nicely with other structural management systems including porous pavement parking lots, infiltration trenches, and non-structural stormwater BMPs. Bioretention areas typically require little maintenance once fully established and often replace areas that were intensively landscaped and required high maintenance.

A Stormwater Planter is a container or enclosed feature located either above ground or below ground, planted with vegetation that captures stormwater within the structure itself.

BENEFITS

- Volume control & GW recharge, moderate peak rate control
- Versatile w/ broad applicability
- Enhanced site aesthetics and habitat
- Potential air quality & climate benefits

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Yes (Planters)
Industrial	Yes
Retrofit	Yes
Recreational	Yes
Public/Private	Yes



Conceptual cross-section showing planter with infiltration

VARIATIONS

- Subsurface storage/infiltration bed
- Use of underdrain and/or impervious liner
- Planters – Contained (above ground), infiltration (below ground), flow-through
- Pre-treatment incorporated into design

KEY DESIGN FEATURES

- Ponding depths 6 to 18 inches for drawdown within 48 hours
- Plant selection (native vegetation that is tolerant of hydrologic variability, salts, and environmental stress)
- Amended or engineered soil as needed
- Stable inflow/outflow conditions and positive overflow for extreme storm events
- Planters may require flow bypass during winter
- Planters - Captured runoff to drain out in 3 to 4 hours after storm even unless used for irrigation

SITE FACTORS

- Water Table/ Bedrock Separation: 2-foot minimum, 4-foot recommended (N/A for contained planter)
- Soils: HSG A and B preferred; C & D may require an underdrain (N/A for contained planter)
- Feasibility on steeper slopes: medium
- Potential Hotspots: yes with pretreatment and/or impervious liner, yes for contained planter
- Maximum recommended drainage area loading: 15:1; not more than 1 acre to one rain garden

MAINTENANCE

- Often requires watering during establishment
- Spot weeding, pruning, erosion repair, trash removal, mulch reapplication (as needed) required 2-3x/growing season
- Maintenance tasks and costs are similar to traditional landscaping

COST

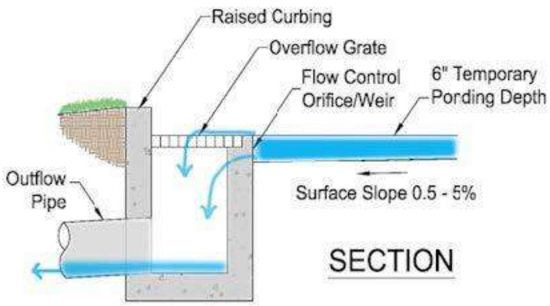
- Bioretention costs will vary depending on size/vegetation type/storage elements; typical costs $10-25/ sq. ft.

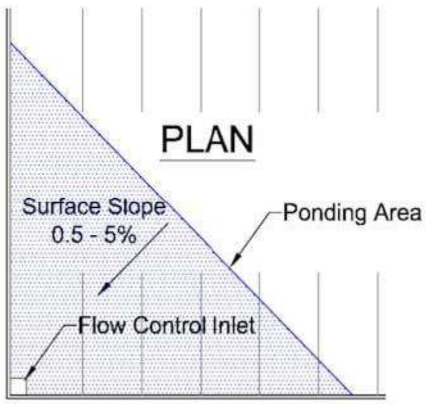
POTENTIAL LIMITATIONS

- Higher maintenance until vegetation is established
- Limited impervious drainage area to each BMP
- Requires careful selection & establishment of plants

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	High	TSS	High	Capital Cost	Medium
Groundwater Recharge	High	TP	High	Maintenance	Low/Medium
Peak Rate	Medium	TN	Medium	Winter Performance	Medium
Erosion Reduction	Medium	Temperature	Medium/High	Fast Track Potential	Medium
Flood Protection	Medium			Aesthetics	High

FACT SHEET: BLUE STREETS





Blue streets refer to the practice of temporarily detaining stormwater, delaying its release and reducing its peak flow rate into the storm sewer system.

Surface storage practices have been used traditionally on rooftops (i.e. blue roofs) and in parking lots but can also be implemented in residential streets and right-of-ways with lower traffic volumes. These "blue streets" can be a cost-effective way to manage stormwater and address surcharging without significant subsurface excavation and construction interventions.

Surface storage is typically accomplished using drainage structures and retrofitting existing catch basins to feature devices such as orifice restrictors or vortex restrictors. Blue streets also emphasize minimizing the number of catch basins to the extent practical.

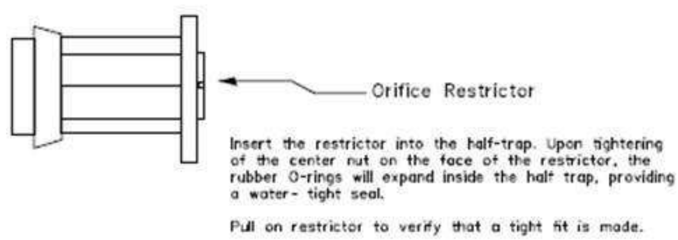
Blue streets (surface storage techniques) are often best implemented in alleys, low volume roads, and on private sites, for public perception and safety reasons.

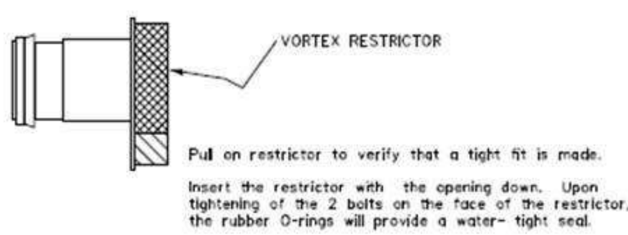
BENEFITS

- Reduces stress on drainage system
- Mitigates peak rate flow
- Cost-effective technique to manage stormwater
- Short duration storage
- Reduces need for subsurface excavation and construction

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Limited
Industrial	Yes
Retrofit	Yes
Highway/Road	Limited for Highway
Recreational	Yes
Public/Private	Yes/Yes

DRAINAGE STRUCTURES RESTRICTORS





Drainage structure restrictors are key features of surface storage and blue streets. Source: City of Chicago design manual

VARIATIONS

- Flow control structures
- Orifice restrictors
- Vortex restrictors
- Reduction in number of catch basins/inlets on a street

KEY DESIGN FEATURES

- Emergency overflows typically required
- Maximum ponding depths (less than one foot)
- Adequate surface slope to outlet
- Traffic volume, public safety, and user inconvenience must be taken into account

SITE FACTORS

- Water table to bedrock depth – N/A
- Soils – N/A
- Slope – Requires relatively low slopes to provide appreciable storage
- Potential hotspots – yes
- Maximum drainage area – relatively small DA to individual inlets (similar to conventional inlets)

MAINTENANCE

- Clean drainage structures and repair/replace parts as needed

COST

- Drainage structures restrictors range in cost, for example installing a vortex restrictor can be approximately $1000 per inlet

POTENTIAL LIMITATIONS

- Not suitable for heavily-used roadways without adequate median/shoulder space
- Excess ponding on roadways may freeze in winter conditions
- Public safety perceptions and concerns
- Does not inherently address water quality and quantity – should generally be combined with other BMPs

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Low	TSS	Low	Capital Cost	Low
Groundwater Recharge	Low	TP	Low	Maintenance	Low/Medium
Peak Rate	Medium	TN	Low	Winter Performance	Medium
Erosion Reduction	Low	Temperature	Low	Fast Track Potential	High
Flood Protection	Medium			Aesthetics	Low

FACT SHEET: CISTERNS/RAIN BARRELS

Example of above-ground cistern with vegetation screening

Cisterns (or rain barrels) are structures designed to intercept and store runoff from rooftops to allow for its reuse, reducing volume and overall water quality impairment. Stormwater is contained in the cistern structure and typically reused for irrigation or other water needs. This GI technology reduces potable water needs while also reducing stormwater discharges.

Cisterns can be located above or below ground and are containers or tanks with a larger storage capacity than a rain barrel, and often used to supplement grey water needs (i.e. toilet flushing) in a building, as well as irrigation. Rain barrels are above-ground structures connected to rooftop downspouts that collect rainwater and store it until needed for a specific use, such as landscape irrigation.

Cisterns and rain barrels can be used in suburban and urban areas where the need for supplemental onsite irrigation or other high water uses is especially apparent.

BENEFITS

- Provides supplemental water supply
- Wide applicability
- Reduces potable water use
- Related cost savings and environmental benefits
- Reduces stormwater runoff impacts

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Yes, if demand exists
Industrial	Yes
Retrofit	Yes
Highway/Road	No
Recreational	Limited
Public/Private	Yes/Yes

Rain barrel prototype example

VARIATIONS

- Cisterns – can be either underground and above ground
- Water storage tanks
- Storage beneath a usable surface using manufactured stormwater products (chambers, pipes, crates, etc.)
- Various sizes, materials, shapes, etc.

KEY DESIGN FEATURES

- Small storm events are captured with most structures
- Provide overflow for large storms events
- Discharge/use water before next storm event
- Consider site topography, placing structure upgradient of plantings (if applicable) in order to eliminate pumping needs

SITE FACTORS

- Water table to bedrock depth – N/A (although must be considered for subsurface systems)
- Soils – N/A
- Slope – N/A
- Potential hotspots – typically N/A for rooftop runoff
- Maximum drainage area – typically relatively small, based on storage capacity

MAINTENANCE

- Use stored water and/or discharge before next storm event
- Clean annually and check for loose valves, leaks, etc. monthly during active season
- May require flow bypass valves or be taken offline during the winter

COST

- Cisterns typically cost from $3 to $8/gallon/ Rain Barrels range from $75 to $300 each

POTENTIAL LIMITATIONS

- Manages only relatively small storm events which requires additional management and use for the stored water.
- Typically requires additional management of runoff
- Requires a use for the stored water (irrigation, gray water, etc.)

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Low/Medium	TSS	Medium	Capital Cost	Medium
Groundwater Recharge*	Low/Medium	TP	Medium	Maintenance	Medium
Peak Rate*	Low	TN	Low	Winter Performance	Low
Erosion Reduction	Low	Temperature	Low	Fast Track Potential	Medium/High
Flood Protection*	Low			Aesthetics	Low/Medium

**Although stand-alone cisterns are expected to have lower benefits in these categories, if combined with downspout disconnection to landscaped areas the benefits can be increased significantly.*

FACT SHEET: VEGETATED (GREEN) ROOFS AND BLUE ROOFS

Green roof (Philadelphia, PA)

Blue roof (NYC) / Photo – Gowanus Canal Conservancy

A green roof is a veneer of vegetation that is grown on and covers an otherwise conventional flat or pitched roof, endowing the roof with hydrologic characteristics that more closely match surface vegetation. The overall thickness of the veneer typically ranges from 2 to 6 inches and may contain multiple layers, such as waterproofing, synthetic insulation, non-soil engineered growth media, fabrics, and synthetic components. Vegetated roofs can be optimized to achieve water quantity and water quality benefits. Through the appropriate selection of materials, even thin vegetated covers can provide significant rainfall retention and detention functions.

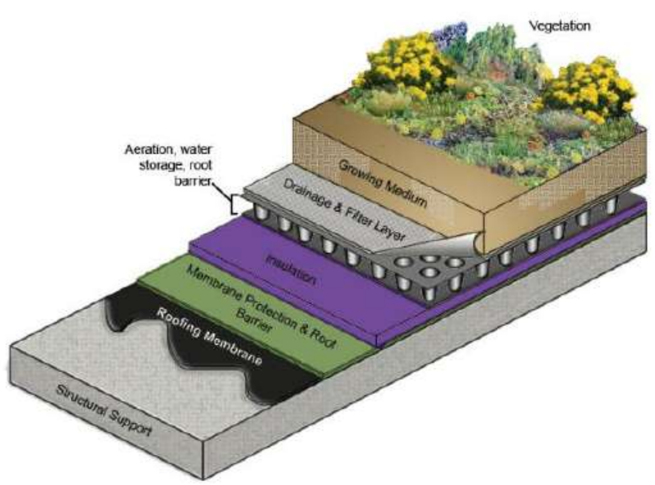
Depending on the plant material and planned usage for the roof area, modern vegetated roofs can be categorized as systems that are intensive (usually > 6 inches of substrate), semi-intensive, or extensive (<4 inches). More maintenance, higher costs and more weight are the characteristics for the intensive system compared to that of the extensive vegetated roof.

Another GI rooftop technology - **Blue roofs -** are non-vegetated systems that employ stormwater control devices to temporarily store water on the rooftop and then release it into the drainage system at a relatively low flow rate. Storage can be provided by modifying roof drains or through the use of detention trays that sometimes have a lightweight gravel media. Blue roof and green roof technologies can also be combined in a design to achieve

BENEFITS

- High volume reduction (annual basis)
- Moderate ecological value and habitat (green roofs)
- High aesthetic value (green roofs)
- Energy benefits (heating/cooling)
- Urban heat island reduction

POTENTIAL APPLICATIONS	
Residential	Limited
Commercial	Yes
Ultra-Urban	Yes
Industrial	Yes
Retrofit	Yes
Highway/Road	No
Recreational	Limited
Public/Private	Yes/Yes



Cross-section showing components of vegetated roof system

VARIATIONS

- Green roofs - single media system, dual media system (with synthetic liner)
- Green roofs - Intensive, Extensive, or Semi-intensive

KEY DESIGN FEATURES

- Engineered media should have a high mineral content and is typically 85% to 97% nonorganic.
- 2-6 inches of non-soil engineered media; assemblies that are 4 inches and deeper may include more than one type of engineered media.
- Irrigation is generally not required (or even desirable) for optimal stormwater management
- Internal building drainage, including provision to cover and protect deck drains or scuppers, must anticipate the need to manage large rainfall events without inundating the vegetated roof system.
- Assemblies planned for roofs with pitches steeper than 2:12 (9.5 degrees) must incorporate supplemental measures to insure stability against siding.
- The roof structure must be evaluated for compatibility with the maximum predicted dead and live loads. Typical dead loads for wet extensive vegetated covers range from about 12 to 36 pounds per square foot.
- Waterproofing must be resistant to biological and root attack. In many instances a supplemental root barrier-layer is installed to protect the primary waterproofing.
- Blue roofs: roof structure, waterproofing, accommodation for larger storm events/emergency overflows

MAINTENANCE

- Once vegetation is fully established, little maintenance needed for the extensive system
- Maintenance cost is similar to native landscaping, $0.10-$0.35 per square foot
- Blue roof maintenance is similar to conventional roof maintenance (cleaning roof and drains as necessary)

COST

- Green roofs: $10 - $35 per square foot, including all structural components, soil, and plants; more expensive than traditional roofs, but have longer lifespan; generally less expensive to install on new roof versus retrofit on existing roof
- Blue roofs: Typically add only $1-$5 per square foot compared to traditional roofs

POTENTIAL LIMITATIONS

- Green roofs have higher maintenance needs until vegetation is established
- Need for adequate roof structure and waterproofing; can be challenging on retrofit application

STORMWATER QUANTITY FUNCTIONS*		STORMWATER QUALITY FUNCTIONS*		ADDITIONAL CONSIDERATIONS	
Volume	Medium/High	TSS	Low/Medium	Capital Cost	High
Groundwater Recharge	Low	TP	Low/Medium	Maintenance	Medium
Peak Rate	Medium	TN	Low	Winter Performance	Medium
Erosion Reduction	Low/Medium	Temperature	Medium	Fast Track Potential	Low
Flood Protection	Low/Medium			Aesthetics	High

**For green roofs, blue roofs primarily function for peak rate control and flood protection.*

FACT SHEET: POROUS PAVEMENT

Porous asphalt basketball courts (Lancaster, PA)

Porous (pervious) pavement is a Green Infrastructure (GI) technique that combines stormwater infiltration, storage, and a structural pavement consisting of a permeable surface underlain by a storage/infiltration bed. Porous pavement is well suited for parking areas, walking paths, sidewalks, playgrounds, plazas, basketball courts, and other similar uses.

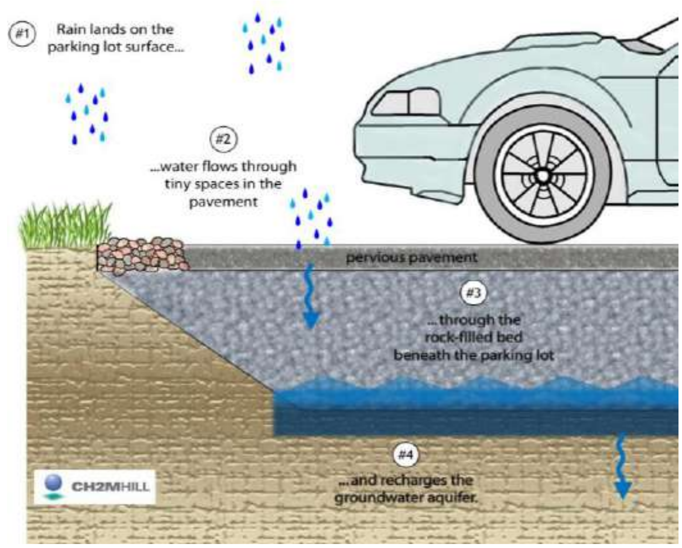
A porous pavement system consists of a pervious surface course underlain by a storage bed, typically placed on uncompacted subgrade to facilitate stormwater infiltration. The subsurface storage reservoir may consist of a stone bed of uniformly graded, clean and washed course aggregate with a void space of approximately 40% or other manufactured structural storage units. Porous pavement may be asphalt, concrete, permeable paver blocks, reinforced turf/gravel, or other emerging types of pavement.

BENEFITS

- Volume control & GW recharge, moderate peak rate control
- Versatile with broad applicability
- Dual use for pavement structure and stormwater management
- Pavers come in range of sizes and colors
- Opportunity for public education/demonstration

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra Urban	Yes
Industrial	Limited
Retrofit	Yes
Highway	Limited
Recreational	Yes
Public/Private	Yes/Yes

Porous pavers (San Diego)



Conceptual diagram showing how porous pavement functions

KEY DESIGN FEATURES

- Soil testing required for infiltration designs
- Limit amount of adjacent areas that drain directly onto the surface of the porous pavement
- Uncompacted soil subgrade for infiltration
- Level storage bed bottoms
- Provide positive storm water overflow from bed
- Surface permeability greater than 20 inches per hour
- Secondary inflow mechanism recommended
- Pretreatment for sediment-laden runoff, limit sources of sediment/debris deposition

SITE FACTORS

- Water Table/Bedrock Separation: 2-foot minimum
- Soils: HSG A&B preferred; HSG C&D may require underdrains
- Feasibility on steeper slopes: Low
- Potential Hotspots: Not without design of pretreatment system/impervious liner

MAINTENANCE

- Clean inlets
- Vacuum biannually
- Maintain adjacent landscaping/planting beds
- Periodic replacement of aggregate in paver block joints (if applicable)
- Careful winter maintenance (no sand or other abrasives, careful plowing)

COST

- Varies by porous pavement type
- Local quarry needed for stone filled infiltration bed
- Typically $7-$15 per square foot, including underground stormwater storage bed
- Generally more than standard pavement, but saves on cost of other BMPs and traditional drainage infrastructure

POTENTIAL LIMITATIONS

- Careful design & construction required
- Pervious pavement not suitable for all uses/not suitable for steep slopes
- Higher maintenance needs than standard pavement

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	High	TSS*	High	Capital Cost	Medium
Groundwater Recharge	High	TP	High	Maintenance	Medium
Peak Rate	Medium/High	TN	Medium	Winter Performance	Medium/High
Erosion Reduction	Medium/High	Temperature	High	Fast Track Potential	Low/Medium
Flood Protection	Medium/High			Aesthetics	Low to High

** While porous pavements typically result in low TSS loads, sources of sediment should be minimized to reduce the risk of clogging.*

FACT SHEET: SOIL AMENDMENTS

Healthy soils help vegetation thrive while also increasing soil infiltration rates Photo: S.Coronado

Soil amendments can include a variety of practices that reduce the generation of runoff by improving vegetation growth, increasing water infiltration, and improving water holding capacity. For example, on existing turf grass, soil amendments can include placing a thin layer of compost or other materials and spreading them evenly over existing vegetation. Amendments on existing turf grass areas can be applied for several years to improve soil over time. Soil testing can indicate how many applications are appropriate. Existing grass areas can also be aerated to improve water transmission and allow for deeper incorporation of compost.

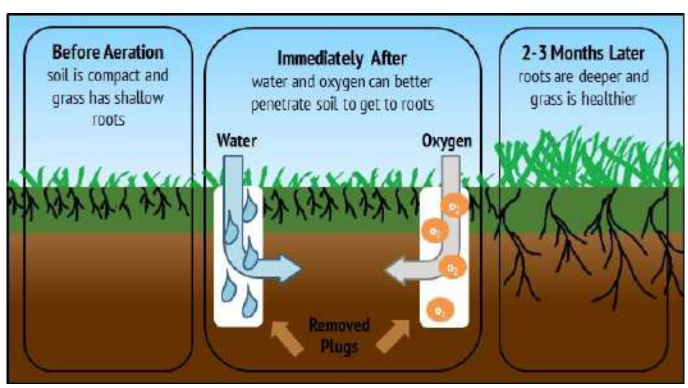
On new construction, redevelopment, and restoration projects, compost can be applied and deeply tilled into compacted soils to restore their porosity before the areas are re-vegetated (potentially with native landscaping, combining the benefits of both GI strategies).

BENEFITS

- Enhanced soil health and vegetation growth/root depth
- Improved soil infiltration rates
- Enhanced soil water holding capacity
- Reduced stormwater runoff from soil surface

POTENTIAL APPLICATIONS	
Residential	Yes
Commercial	Yes
Ultra-Urban	Limited
Industrial	Yes
Retrofit	Yes
Highway/Road	Yes
Recreational	Yes
Public/Private	Yes/Yes

A variety of soil amendments are available depending on the specific soil conditions and desired result. Photo: Pahls Market



Physical aeration (tilling) can also help improve soil health and soil permeability/porosity. Image: GreenMaxLawns

VARIATIONS

- Treating turf grass or areas with more intensive plant palettes
- Combining amended soil areas with downspout disconnection
- Physical aeration/tilling of turf grass/vegetated areas can help to remedy soil compaction
- Compost, sand, microbes, mycorrhizae, gypsum, biochar, manure, worm castings, etc.
- Amendments can improve soil aggregation, increase porosity, and improve aeration and rooting depth

KEY DESIGN FEATURES

- Soil bulk density and soil nutrient testing required
- Existing soil conditions should be evaluated before forming an amendment strategy

SITE FACTORS

- Water table to bedrock depth – N/A
- Soils – Bulk density and nutrient levels
- Slope – Not recommended for use on slopes greater than 3:1
- Potential hotspots – N/A
- Maximum drainage area – N/A

MAINTENANCE

- Replenishment of amendments on a regular basis may be required
- Aeration of soil often done at same time

COST

- The cost of soil amendments ranges widely depending on the size and type. Larger projects are estimated to cost approximately $5,000 per acre.

POTENTIAL LIMITATIONS

- Viability depends upon soil testing results
- Certain types of soil may not be favorable for success with amendments
- Not a regulated industry – testing of amendment may be needed to ensure specifications
- Physical aeration should not be done near existing tree roots

STORMWATER QUANTITY FUNCTIONS		STORMWATER QUALITY FUNCTIONS		ADDITIONAL CONSIDERATIONS	
Volume	Medium	TSS*	Medium	Capital Cost	Low
Groundwater Recharge	Medium	TP*	Medium	Maintenance	Low/Medium
Peak Rate	Medium	TN*	Medium	Winter Performance	Medium
Erosion Reduction	High	Temperature	Low	Fast Track Potential	Medium
Flood Protection	Low/Medium			Aesthetics	Medium

**Water quality benefits expected to vary widely depending on the condition of the soil/landscape prior to soil amendments.*

Appendix D
Alternatives Analysis Results

Appendix D - Alternative Analysis Summary

Tabulation of Solutions, Costs, and Scoring for Cameron Run High-Priority Problem Areas

		Solution Summary			Flood Volume Summary					Weighted Solution Score								
Problem Area ID	Solution Technology (Conveyance, Storage, Low GI, Medium GI, High GI)	Project Name	Cost ($M)	Benefit-Cost Ratio	Existing Flood Volume (MG)	Solution Flood Volume (MG)	Flood Volume Reduction (MG)	Flood Volume Reduction (%)	Cost/Gallon of Flood Reduction ($/gal)	Urban Drainage/ Flooding	Environmental Compliance	EcoCity Goals/ Sustainability	Social Benefits	Integrated Asset Management	City-Wide Maintenance Implications	Constructability	Public Acceptance	Total
501	Low GI	LGI-501	$ 0.020	1945.8	0.03	0.03	0.00	12%	$ 5.80	2.0	2.5	3.7	3.0	0.0	13.0	10.8	4.8	39.7
501	Storage	STOR-501	$ -	0.0	0.03	0.03	0.00	0%	$ -	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
501	Conveyance	CONV-501	$ 0.202	242.1	30.21	-	0.03	100%	$ 6.70	17.1	0.0	0.0	0.0	0.0	16.2	10.8	4.8	49.0
501	High GI	HGI-501	$ 0.185	317.6	30.21	11.03	0.02	64%	$ 9.66	10.9	12.7	3.7	3.0	0.0	13.0	10.8	4.8	58.8
501	Medium GI	MGI-501	$ 0.086	551.4	30.21	21.66	0.01	28%	$ 10.11	4.9	7.6	3.7	3.0	0.0	13.0	10.8	4.8	47.7
502	Conveyance	CONV-502	$ 0.181	255.4	124.12	19.28	0.10	84%	$ 1.73	14.5	0.0	0.0	0.0	0.0	16.2	10.8	4.8	46.3
502	Low GI	LGI-502	$ 0.012	3821.2	0.12	0.11	0.02	12%	$ 0.81	2.1	2.0	4.3	3.4	6.6	13.0	10.8	4.8	46.9
502	Storage	STOR-502	$ -	0.0	0.12	0.12	N/A	0%	N/A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
502	High GI	HGI-502	$ 0.114	545.7	124.12	58.95	0.07	53%	$ 1.75	9.0	10.3	4.3	3.4	6.6	13.0	10.8	4.8	62.1
502	Medium GI	MGI-502	$ 0.052	1046.5	124.12	80.76	0.04	35%	$ 1.21	6.0	6.1	4.3	3.4	6.6	13.0	10.8	4.8	54.9
503	Conveyance	CONV-503	$ 0.554	88.5	1.17	-	0.00	100%	$ 474.23	17.1	0.0	0.0	0.0	0.0	16.2	10.8	4.8	49.0
503	High GI	HGI-503	$ 2.681	26.1	1.17	-	0.00	100%	$ 2,295.80	17.1	10.8	3.8	3.0	6.6	13.0	10.8	4.8	70.0
503	Low GI	LGI-503	$ 0.295	207.7	1.17	-	0.00	100%	$ 252.61	17.1	2.1	3.8	3.0	6.6	13.0	10.8	4.8	61.3
503	Medium GI	MGI-503	$ 1.247	52.6	1.17	-	0.00	100%	$ 1,068.29	17.1	6.4	3.8	3.0	6.6	13.0	10.8	4.8	65.6
503	Storage	STOR-503	$ 0.206	174.5	1.17	-	0.00	100%	$ 176.76	17.1	0.0	0.0	0.0	0.0	3.2	10.8	4.8	36.0
504	Conveyance	CONV-504	$ 0.256	192.1	71.95	-	0.07	100%	$ 3.55	17.1	0.0	0.0	0.0	6.6	16.2	4.3	4.8	49.1
504	High GI	HGI-504	$ 0.971	73.2	71.95	-	0.07	100%	$ 13.50	17.1	15.5	5.4	4.3	6.6	13.0	4.3	4.8	71.1
504	Low GI	LGI-504	$ 0.107	420.5	0.07	0.06	0.02	21%	$ 6.93	3.7	3.0	5.4	4.3	6.6	13.0	4.3	4.8	45.1
504	Medium GI	MGI-504	$ 0.452	130.7	71.95	23.68	0.05	67%	$ 9.37	11.5	9.1	5.4	4.3	6.6	13.0	4.3	4.8	59.1
504	Storage	STOR-504	$ 0.320	130.0	71.95	4.32	0.07	94%	$ 4.74	16.1	0.0	0.0	0.0	13.2	3.2	4.3	4.8	41.7
505	Conveyance	CONV-505	$ 0.204	181.4	23.42	-	0.02	100%	$ 8.72	11.7	0.0	0.0	0.0	0.0	16.2	4.3	4.8	37.0
505	High GI	HGI-505	$ 0.174	316.6	23.42	0.01	0.02	100%	$ 7.41	17.1	9.2	3.6	2.9	0.0	13.0	4.3	4.8	54.9
505	Storage	STOR-505	$ -	0.0	0.02	0.02	0.00	0%	$ -	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
505	Low GI	LGI-505	$ 0.019	1881.4	23.42	15.75	0.01	33%	$ 2.50	5.6	1.8	3.6	2.9	0.0	13.0	4.3	4.8	36.1
505	Medium GI	MGI-505	$ 0.081	598.1	23.42	4.10	0.02	82%	$ 4.18	14.1	5.5	3.6	2.9	0.0	13.0	4.3	4.8	48.3
506	Conveyance	CONV-506	$ 0.429	99.4	104.90	39.19	0.07	63%	$ 6.52	10.7	0.0	0.0	0.0	0.0	16.2	10.8	4.8	42.6
506	High GI	HGI-506	$ 0.561	99.4	104.90	58.44	0.05	44%	$ 12.07	7.6	12.3	4.0	3.2	0.0	13.0	10.8	4.8	55.7
506	Medium GI	MGI-506	$ 0.261	182.1	104.90	78.25	0.03	25%	$ 9.79	4.4	7.3	4.0	3.2	0.0	13.0	10.8	4.8	47.5
506	Low GI	LGI-506	$ 0.062	642.3	0.10	0.10	0.01	8%	$ 7.12	1.4	2.4	4.0	3.2	0.0	13.0	10.8	4.8	39.7
506	Storage	STOR-506	$ -	0.0	0.10	0.11	N/A	-1%	N/A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
507	Conveyance	CONV-507	$ 0.961	44.6	671.64	160.28	0.51	76%	$ 1.88	13.1	0.0	0.0	0.0	6.6	16.2	2.2	4.8	42.8
507	High GI	HGI-507	$ 0.687	72.6	671.64	489.81	0.18	27%	$ 3.78	4.6	11.2	3.0	2.4	6.6	13.0	4.3	4.8	49.9
507	Storage	STOR-507	$ 0.690	44.6	671.64	123.96	0.55	82%	$ 1.26	14.0	0.0	0.0	0.0	6.6	3.2	2.2	4.8	30.8
507	Medium GI	MGI-507	$ 0.319	136.0	671.64	566.16	0.11	16%	$ 3.03	2.7	6.6	3.0	2.4	6.6	13.0	4.3	4.8	43.4
507	Low GI	LGI-507	$ 0.075	492.6	0.67	0.64	0.03	5%	$ 2.20	0.9	2.2	3.0	2.4	6.6	13.0	4.3	4.8	37.2
508	Conveyance	CONV-508	$ 1.960	32.4	1,812.96	6.35	1.81	100%	$ 1.08	15.6	0.0	0.0	2.9	13.2	16.2	10.8	4.8	63.5
508	High GI	HGI-508	$ 3.184	19.3	1,812.96	1,096.08	0.72	40%	$ 4.44	6.8	11.4	3.7	4.4	6.6	13.0	10.8	4.8	61.4
508	Medium GI	MGI-508	$ 1.481	36.3	1,812.96	1,410.44	0.40	22%	$ 3.68	3.8	6.8	3.7	4.4	6.6	13.0	10.8	4.8	53.8
508	Storage	STOR-508	$ 1.529	32.3	1,812.96	278.96	1.53	85%	$ 1.00	14.5	0.0	0.0	2.9	13.2	3.2	10.8	4.8	49.4
508	Low GI	LGI-508	$ 0.351	132.8	1.81	1.69	0.12	7%	$ 2.84	1.2	2.2	3.7	4.4	6.6	13.0	10.8	4.8	46.7

Appendix E
Basis of Cost

City of Alexandria Storm Sewer Capacity Analysis
Planning Level Cost Information

PREPARED FOR:	City of Alexandria Transportation and Engineering Services
COPY TO:	File
PREPARED BY:	CH2M HILL
DATE:	May 15, 2014
PROJECT NUMBER:	240027

Introduction

The City of Alexandria, Virginia, has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of the stormwater capacity analysis project is to provide a program for analyzing storm sewer capacity issues, identifying problem areas, developing and prioritizing solutions, and providing support for public outreach and education. The project is being implemented in phases by watershed. The watersheds include Hooffs Run, Four Mile Run, Holmes Run, Cameron Run, Taylor Run, Strawberry Run, Potomac River, and Backlick Run.

This technical memorandum provides details on the basis of cost estimates developed for each solution and the watershed wide alternatives. The information includes panning level unit cost for conveyance, storage and green infrastructure solutions.

These cost estimates are considered a Class 4 - Planning Level estimate as defined by the American Association of Cost Engineering (AACE), International Recommended Practice No. 18R-97, and as designated in ASTM E 2516-06. It is considered accurate to +50% to -30% based up to a 15% complete project definition.

Definitions

The following cost terminologies are used within this technical memorandum:

- Construction cost: Installed cost, including materials, labor, and site adjustment factors such as overcoming utility conflicts, dewatering, and pavement restoration.
- ENRCCI Cost Adjustment Factor: Cost adjustment factor of 0.9 to adjust cost to October 2013 dollars for the DC-Baltimore metro area
- Service and Contingency Factor (SCF) A factor of 1.4 is applied for this project to account for engineering and design expenses (20%) and for contingency allowance (20%).
- Capital cost: Construction cost multiplied by a Service and Contingency Factor (SCF) to cover engineering and design and contingency allowance.
- Operating cost: Operation and maintenance were not considered for this project.

Gravity Sewer Relief Costs

Conveyance projects were costed on a per linear foot basis, based on pipe size and depth. The construction cost rates ($/ft) for gravity sewer replacement are listed in Table 1. Cost rates are shown for different road types. The Gravity sewer cost rates include complete installation of sewer pipes, inlets/manholes, and other ancillary structures as well as surface restoration. The costs were established through literature review and updated based on an assessment of bid tabulation data from Kansas City metro area between 2008 and 2012, and a comparison to Fairfax County, VA unit cost schedule, March 2013. All costs were adjusted to Washington DC, 2013 dollars using Engineering News-Record Construction Cost Index (ENRCCI) adjustment factors.

Factors are applied to the construction cost of gravity sewer pipe replacement to reflect the cost associated with crossing under streams and railroads as listed in Table 2.

Costs of routine O&M, inspection and cleaning at periodic intervals during the life of the gravity sewer were assumed to part of City-wide facilities maintenance plan and should take place even though those costs are not specifically included here.

TABLE 1
Open Cut Gravity Sewer Construction Costs

		Sewer Construction Cost ($/LF) (1)					
Pipe Diameter (in)	Material	Trench depth up to 10 feet		Trench depth 10 to 15 feet		Trench depth 15 to 20 feet	
		Residential	Arterial	Residential	Arterial	Residential	Arterial
8	PVC	$90	$104	$113	$130	$140	$162
10	PVC	$113	$131	$140	$163	$176	$204
12	PVC	$122	$140	$152	$175	$190	$218
15	PVC	$131	$153	$163	$192	$204	$239
18	PVC	$140	$162	$175	$203	$218	$253
21	PVC	$162	$189	$203	$237	$253	$295
24	PVC	$185	$212	$230	$265	$288	$330
30	RCP	$257	$297	$320	$372	$401	$464
36	RCP	$306	$356	$383	$445	$478	$555
42	RCP	$360	$414	$450	$518	$563	$647
48	RCP	$410	$473	$512	$590	$640	$738
54	RCP	$459	$531	$574	$664	$717	$830
60	RCP	$509	$585	$635	$732	$795	$914
72	RCP	$815	$936	$1,018	$1,170	$1,273	$1,463

(1) Listed construction costs have been adjusted to October 2013 dollars using ENRCCI for the DC-Baltimore Metro area.

TABLE 2
Gravity Pipe Construction Cost Factors

Type of Crossing	Cost Factor
Stream	3
Railroad	7

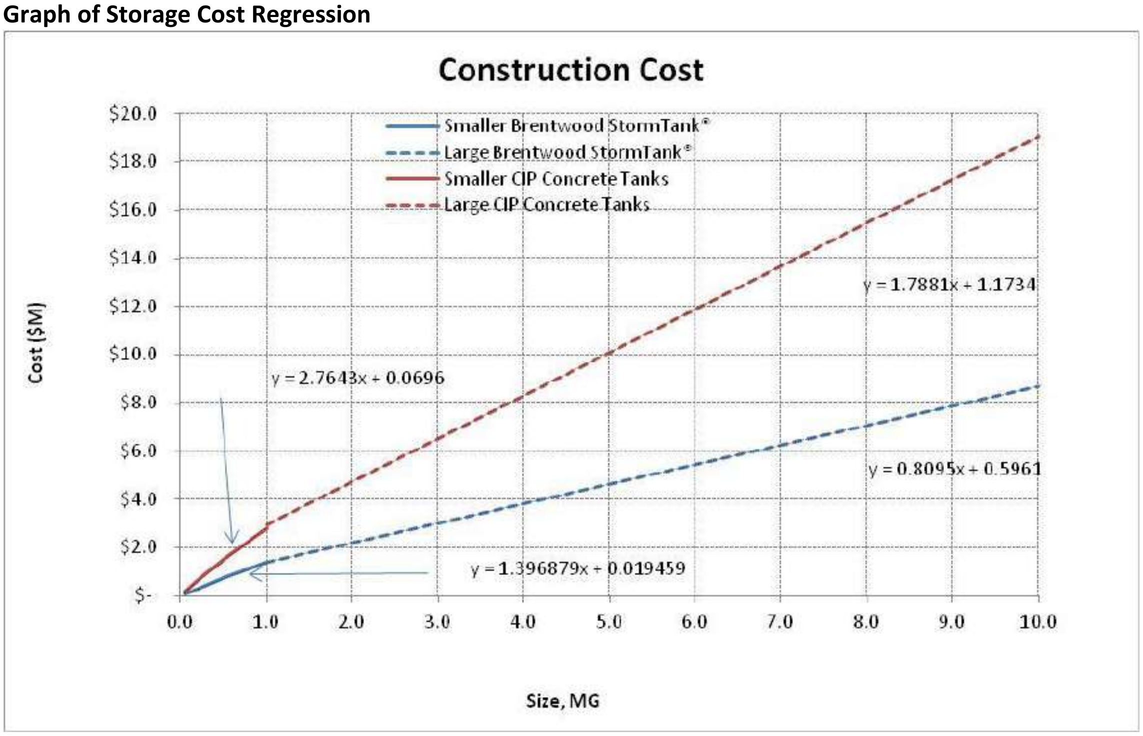
Storage Facility Cost Information

Cost estimates for the storage facilities were developed for two technologies: A traditional underground cast-in-place concrete tank and an alternative stackable modular unit installed underground and wrapped with an impermeable or permeable liner.

The CIP Concrete storage facility construction cost was developed as a customized cost estimate based on CH2M HILL's Program Alternative Cost Calculator (PACC) Tool. The costs are construction costs only and do not include administration costs, engineering costs, contingencies, and other soft costs. The costs for smaller storage units with volumes less than 1 million gallon were found to be high for the CIP concrete tank. Hence, a separate takeoff cost estimate was developed for smaller storage volume; less than 1 million gallons.

A separate cost estimate was developed for the stackable modular units. There is an increasing use of these technologies in the industry and the cost of installation is getting increasingly competitive compared to traditional storage methods. Construction costs were developed based on one such stackable modular unit, StormTank® modules by Brentwood Industries. The cost for the Brentwood StormTank® modules came out significantly less than that for CIP concrete tanks. For the purpose of the evaluation of watershed wide alternative solutions, the StormTank® modules was used as the most cost effective alternative, however site specific conditions will determine which technology will be most appropriate in a given location. For example a site with high water table may make the use of CIP concrete tanks preferable over the StormTank® modules. The estimated construction costs for the CIP concrete tanks and the Brentwood StormTank® are provided in Figure 1.

FIGURE 1
Graph of Storage Cost Regression



The following assumptions were made for storage tank selection and sizing:

1. Offline enclosed underground storage will be active only during wet weather events.
2. Options for odor control were not considered.
3. Costs for storage facilities with intermediate storage volumes were interpolated based on linear regression shown in Figure 1.

Green Infrastructure (GI) Cost Information

A variety of sources and professional judgment were used to develop the GI costs. Where technologies were directly comparable, costs were updated based on Fairfax County, VA unit cost schedule, March 2013. The unit costs used to develop GI implementation cost are included in Table 4. Costs reflecting stand-alone projects (e.g., installing a green roof on top of an existing building) were used for costing alternatives solutions. Incremental costs of adding GI to an existing project can provide significant savings and are provided for reference, but not used directly in cost estimates for this project.

In the CASSCA Project GI is being proposed as a series of GI programs applicable to specific land uses (e.g. green parking is applicable to parking lots). Each GI program may consist of multiple GI technologies which drive the cost of implementing that program. Table 5 lists and the relative amounts of area designated for the GI technologies assumed to be part of each GI program and the resultant unit cost for each GI program.

TABLE 4
Unit Construction Costs of Green Infrastructure Technologies

Green Technology	Stand Alone Cost Proposed for GI Plan ($/GI acre)	Loading Ratio (Ratio of Area Managed to Area of GI)	Stand-Alone Cost Proposed for GI Plan ($/acre managed)	Incremental GI Cost Compared to Stand-Alone
Native Landscaping/Soil Amend.	$ 5,000	1	$ 5,000	50%
Rain Barrels[1] and Native Landscaping/Soil Amend.	$ -	N/A	$ 15,000	90%
Cisterns[2]	N/A	N/A	$ 34,000	90%
Blue Street/Inlet control devices	N/A	N/A	$ 22,500	N/A
Rain Gardens	$ 436,000	12	$ 36,000	70%
Stormwater Trees[3]	$ 34,700	0.5	$ 69,000	50%
Bioswale/Bioretention	$ 1,045,000	12	$ 87,000	70%
Porous Pavement/ Infiltration Trench	$ 436,000	4	$ 109,000	70%
Green Roof[4]	$ 501,000	1	$ 501,000	43%

[1] Each rain barrel is assumed to manage 350 ft^2 of rooftop; therefore, 124.5 barrels are required for 1 acre of roof.
[2] Each 1000-gallon cistern is assumed to manage 6,500 ft^2 of impervious area; therefore, 6.7 barrels are required for 1 acre.
[3] Trees are assumed to have an average 10-foot canopy radius (314 ft^2), with 50 percent assumed to be overhanging impervious area.
[4] Incremental cost of green roofs set to 43 percent to match the District's $5/ ft^2 ($217,800/acre) green roof incentive program.

TABLE 5
Green Infrastructure Technology Elements and Unit Construction Cost of Each Green Program

Green Technology	% Area of Program Assigned to Each GI Technology						
	Blue Streets	**Green Alley**	**Green Buildings**	**Green Parking**	**Green Roofs**	**Green Schools**	**Green Schools**
Native Landscaping/Soil Amend.	-	-		-	-	-	-
Rain Barrels[1] and Native Landscaping/Soil Amend.	-	-	30%	-	-	-	-
Cisterns	-	-	10%	-	-	-	-
Blue Street/Inlet control devices	100%					-	-
Rain Gardens	-	-	30%	-	-	-	-
Stormwater Trees	-	-		-	-	-	30%
Bioswale/Bioretention	-	-	30%	50%	-	65%	30%
Porous Pavement/ Infiltration Trench	-	100%		50%	-	30%	40%
Green Roof	-	-	-	-	100%	5%	-
Unit Cost ($/acre managed)	**$22,500**	**$109,000**	**$44,800**	**$98,000**	**$501,000**	**$114,300**	**$90,400**

Three levels of green infrastructure implementation were evaluated for this project:

- High Implementation – Manage 50% of total impervious area in the shed
- Medium Implementation – Manage 30% of total impervious area in the shed
- Low Implementation – Manage 10% of total impervious area in the shed

The unit cost of implementing GI at the various implementation levels is driven by the availability of GI opportunity areas. As the area available to achieve a GI implementation level become scarce, the cost to achieve that level on GI implementation also increases. It was assumed that GI implementation would focus, in succession, from the most to the least cost effective programs and technologies. That is, for each level of GI implementation the most cost effective program and technologies would be implemented first until the available opportunities for those programs are exhausted. If the level of implementation is not achieved with the most cost effective program, the next most cost effective program is considered in that order until the desired level of GI implementation is achieved. Therefore Low Implementation would be more cost effective (lower cost per acre managed). The unit cost for each implementation level was computed separately for each watershed based on the cost information presented above and the distribution of areas available for GI implementation.

Green Opportunities

Opportunities for blue streets, green streets and alleys, green buildings, green parking, green roofs, and green schools were identified by completing a desktop analysis using the City's 2011 basemap data, including:

- Roads (Road_y and Road_lc)
- Buildings (Blds_y)
- Parking lots (Parking_y)
- Zoning (Zoning_y)
- Parcels (Parcels_y)

The approach to identifying potential opportunities for each program is provided below. All opportunities were combined into a single shapefile of polygons with an attribute for area calculated in acres.

Blue Streets

Local or Residential roads with an average slope less than or equal to 1% and a maximum slope less than or equal to 3%. Road slope was estimated using ArcGIS 3D Analyst tools and the Road_lc feature and City of Alexandria DEM as inputs.

Green Streets and Alleys

Green streets and alleys were identified using the Road_lc and Road_y features to identify roads classed as Arterial, Primary Collector, Residential Collector, Local, and Alley with an average slope less than or equal to 5%. Roadways that fall within school parcels were removed from this layer because they are included in the Green Schools program. Road slope was estimated using ArcGIS 3D analyst tools and the Road_lc feature and City of Alexandria DEM as inputs.

Green Buildings

Green buildings opportunities include buildings where disconnection may be possible. Based on a windshield survey of Taylor Run, approximately 50% of residential buildings, not including single family detached homes, may have opportunities for downspout disconnection. To identify these opportunities, buildings with a BUSE of '1-Residential' were selected from the Blds_y features to identify all residential buildings. This selection was narrowed to apartment buildings and larger residential developments, removing detached houses (BTYPE = 'Detached house'), buildings with less than 5 units (BUNITS < 5), as well as removing nursing homes, hotels, and detention centers. Residential buildings on school properties were also removed because those are accounted for in the Green Schools program. Buildings with a footprint greater than 20,000 square feet were also removed because these buildings are likely too large for a disconnection program.

The footprint of the final selection was reduced by approximately 50% (based on the result of the Taylor Run windshield survey) to approximate the total area of impervious surfaces that could potentially be managed through a disconnection program.

Green Parking

Green parking opportunities were identified as parking lots in the Parking_y feature class with a parking area over 3,000 square feet. Parking lots on school parcels were removed from this selection because they are accounted for in the Green Schools program.

Green Roofs

Green roof opportunities were identified by selecting buildings in the Blds_y feature class with a footprint over 20,000 ft^2 that have a building use (BUSE) of Commercial, Industrial, Institution, Transportation, and Multiple or Mixed use. Also included were buildings over 20,0000 ft^2 that were within a Commercial, Industrial, Coordinated Development District, or Mixed Use zone based on the Zoning_y feature class, unless those buildings were garage/sheds. Buildings on school parcels were removed from this selection because they are accounted for in the Green Schools program.

Green Schools

School parcels were identified by selecting all parcels with a land description (LANDDESC) of 'ED. PUBLIC SCHOOLS', 'PRIVATE ED ENSTS.', or 'ST. ED. INSTITUTIONS' or with an owner name or address that indicated it was school property. School buildings with potential for green roofs were identified by selecting all buildings on school parcels or buildings in the Blds_y features with the word 'school' in the building name (BNAME) or building campus (BCAMPUS) fields where the footprint is over 3,000 ft^2. All remaining impervious surfaces on the school parcels (roads, sidewalks, small buildings, recreation facilities, etc.) were identified as opportunities for green schools.